Bulletin
of
The Geological Society of America

VOLUME 56 August 1945 NUMBER 8

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Subscription, $10 per year.

Publication Office: Mt. Royal and Guilford Aves., Baltimore 2, Md.

Communications for publication should be addressed to The Geological Society of America, Dr. H. R. Aldrich, Secretary, 419 West 117th Street, New York 27, N. Y.

NOTICE.—In accordance with the rules established by the Council, claims for non-receipt of the preceding number of the Bulletin must be sent to the Secretary of the Society within three months of the date of the receipt of this number in order to be filled gratis.

Entered as second-class matter in the Post-Office at Baltimore, Md., under the Act of Congress of July 16, 1894.

Accepted for mailing at special rate of postage provided for in Section 1103 Act of October 3, 1917, authorized on July 8, 1918.

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PETROGRAPHY OF THE WALLIS ISLANDS. By Gordon A. Macdonald

CALCAREOUS ALGAE OF THE UPPER LEADVILLE LIMESTONE NEAR GLENWOOD SPRINGS, COLORADO. By J. H. Johnson

VOLCANISM AND PETROGENESIS AS ILLUSTRATED IN THE HAWAIIAN ISLANDS: Discussion of origin of melilite-nepheline basalts in the Pacific. By Harold T. Stearns

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 56, PP. 783-788, 2 PLS., 3 FIGS. AUGUST 1945

DECADENT CORAL REEF ON ENIWETOK ISLAND, MARSHALL GROUP

BY HAROLD T. STEARNS

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ABSTRACT

The fringing reef on Eniwetok Island consists of four zones, which in seaward order are (1) beach conglomerate; (2) beveled limestone platform; (3) pool and pothole zone; and (4) Lithothamnium ridge. The ridge is honeycombed and channelled rather than a series of miniature terraces typical of such reefs elsewhere in the Pacific. Live corals are scarce, and inland of the ridge the reef is wave-eroded limestone. The hypothesis is offered that a very late local change of level of a few feet in the Marshall Islands caused the decadence of the reef.

INTRODUCTION

The coral reef bordering Eniwetok Island in Eniwetok Atoll, Marshall group, was studied by the writer in June 1944. The island is about 2100 feet wide and 14,400 feet long (Fig. 1). The highest point is about 10 feet above mean sea level. It is a typical atoll island, composed chiefly of fragments of shells and cobbles derived from

the reef and a small proportion of comminuted coral. Foraminifera are also abundant. Beach rock borders much of the shore.

The mean tidal range is 2.8 feet. Most of the reef is dry at low tide but is covered with 2–2.5 feet of water at high tide.

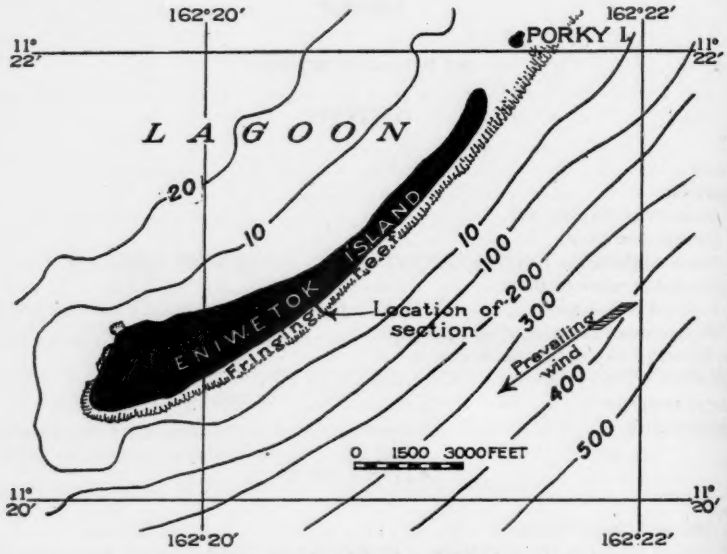

FIGURE 1.—*Map of Eniwetok Island*

Showing location of section in Figure 2 and depth of water in fathoms

CHARACTER OF THE OUTER REEF

GENERAL DESCRIPTION

The fringing reef bordering the eastern or outer windward shore of the island and atoll is composed of four well-defined parallel zones. In order seaward, they are (1)

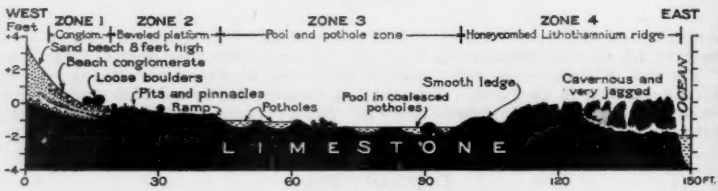

FIGURE 2.—*Section of fringing reef on east side of Eniwetok Island, Marshall group, Western Pacific Ocean*

Showing the four zones at low tide

beach conglomerate 5 to 20 feet wide; (2) beveled limestone platform 50 to 150 feet wide; (3) pool and pothole zone 20 to 100 feet wide; and (4) honeycombed Lithothamnium ridge 20 to 50 feet wide (Fig. 2; Pl. 1, fig. 1).

BEACH CONGLOMERATE

The beach conglomerate is a firmly cemented rock now being destroyed by wave action (Pl. 1, fig. 2). It is composed chiefly of wave-rounded pebbles, cobbles, and boulders of coral and coralline algae in a matrix of sand, broken shells, and echinoderm spines. Beds of sandy limestone are scarce. The grade size of the components parallel closely the size of the unconsolidated debris on the beach above it indicating that wave action had approximately the same intensity when the conglomerate was formed as at present. In places the beach conglomerate is absent or buried under the loose beach deposits. In other places, especially along the south end of the island, the conglomerates contain closely packed wave-worn coral heads up to 3 feet in diameter. The bottom of the beach rock is not exposed, but drilling in the leeward shore has shown that it usually is less than 6 feet thick and offshore may be only 1–2 feet thick. In some places the bedding is sufficiently distinct to show that the beach rock dips 2°–5° seaward from the beach. It is similar to the beach conglomerates on most tropical islands and is believed to be Recent. Before troop occupation, the island was covered with vegetation. Organic acids and ground water, elements usually found associated with beach rock (Stearns and Vaksvik, 1935, p. 41–43), are present in the calcareous sands.

BEVELED LIMESTONE PLATFORM

Seaward of the beach conglomerate and continuous with it is a platform of limestone, varying probably less than half a foot from horizontal, which is dry at low tide (Fig. 2, zone 2). Projecting a few inches above its general level are sharp limestone pinnacles, and indenting its surface are pans a few inches deep, many of which contain pebbles and boulders. Near the shore this platform is largely cemented reef detritus, chiefly of sand size, and not essentially different from the contiguous beach conglomerate except that in places it apparently contains fossil algae and coral in their original position of growth. Little marine life lives on it now, apparently because of thorough drying twice a day during low tides. A few sea slugs live in the shallow pans. The surface of the platform has been scoured and polished by sand and other detritus. The small projecting pinnacles are evidence of the erosion of a platform that formerly stood several inches higher.

Many reefs in the Pacific are composed of beveled calcareous sedimentary rocks, nearly or entirely free of corals in position of growth except at the outer edge. Such reefs are probably in most places the exposed basement of thin coral reefs that grew during the 5- and 25-foot stands of the sea, the upper coralliferous parts having been eroded away as the sea dropped to its present level.

POOL AND POTHOLE ZONE

The outer edge of the beveled platform terminates abruptly in many places in a seaward sloping ramp 1–2 feet high full of potholes commonly containing one or more cobbles or niggerheads which rotate at high tide and slowly enlarge the holes (Fig. 2, zone 3). In a few places the potholes have coalesced transversely to the reef forming sinuous grooves 6–12 inches deep that die out inshore. The pool seaward of this zone contains clusters of cobbles and pebbles and 1 to 1½ feet of water at low tide (Pl. 2,

fig. 1). The pool extends continuously lengthwise of the reef. The floor of the pool resulted from the coalescence of potholes, similar to the process now in progress. A few live encrusting corals inhabit the pool. The outer edge of the pool terminates in a steep ledge of polished and potholed dead nullipore reef. The pool and pothole zone is bare clean limestone, practically free from seaweed. At high tide waves break with great force over the Lithothamnium ridge. The pool and pothole zone invades the ridge in narrow bays and in places extends nearly to the breaker zone.

The pool is obviously deepening, and possibly a barrier reef with an inner lagoon is developing here. A break in the ridge at both ends of the island would result in the development of powerful longshore currents during falling tides which would induce more rapid scour in the pool zone. A fairly rapid rise in sea level of a few feet would convert this fringing reef into a barrier reef with an inner lagoon because the Lithothamnium ridge would grow upward with the rising sea level, while the inner reef flat, barren of marine life and subject to scour, would either remain at its present level or become wider and deeper.

HONEYCOMBED LITHOTHAMNIUM RIDGE

The outer zone is the Lithothamnium ridge which rises abruptly 2–3 feet above the surface of the pool zone. It is extremely rugged, honeycombed, and channelled (Fig. 2, zone 4). Waves breaking at its outer edge at low tide lose their force in the coarsely honeycombed limestone. Live corals are scarce except on the ridge between Eniwetok and Porky islands. The corals are chiefly heavy low branching or encrusting types. Huge purple-spined echinoderms abound in the holes, many with spines 5 inches or more long. The ridge is coated with a greenish-brown seaweed. Nullipores still live and in places form heavy masses. Mollusca are relatively scarce. In normal weather it is dangerous to stand at the outer edge of the ridge even at low tide, as large breakers crash at intervals with tremendous force. The pinnacled, honeycombed, fissured character of the ridge indicates that it is being destroyed (Pl. 2, fig. 2). Figure 3 of Plate 2 shows, for comparison, the terraced form of a healthy Lithothamnium ridge on Tongatabu Island in the Tonga group. Similar healthy ridges are found on the shores of the southern Marianas Islands.

The outer edge of the ridge drops into deep blue water. Soundings by the Navy indicate a 10-fathom shelf about 1000 feet wide beyond which the ocean floor drops rapidly in $3\frac{3}{4}$ miles to a depth of 1000 fathoms. On the outer slope of the ridge in deeper water, nullipores and coral must be thriving to account for the large boulders of these materials cast shoreward. Among the boulders are a few large, black, pitted blocks 3 to 5 feet in diameter that are fragments of the decadent Lithothamnium ridge torn loose by storms.

REEF BETWEEN PORKY AND ENIWETOK ISLANDS

The character of the reef in the channel between Porky and Eniwetok islands is shown in Figure 3. Strong currents carrying gravel and sand have scoured a flat that slopes toward the lagoon. On the west side of the flat, the water is 3–4 feet deep at

FIGURE 1. GENERAL VIEW OF FRINGING REEF
Eastern side of Eniwetok Island. Photo by Naval Construction Battalion.

FIGURE 2. BEDDED SANDY BEACH CONGLOMERATE BEING DESTROYED BY WAVE ACTION
Photo by Naval Construction Battalion.

REEF AND BEACH CONGLOMERATE, ENIWETOK ISLAND

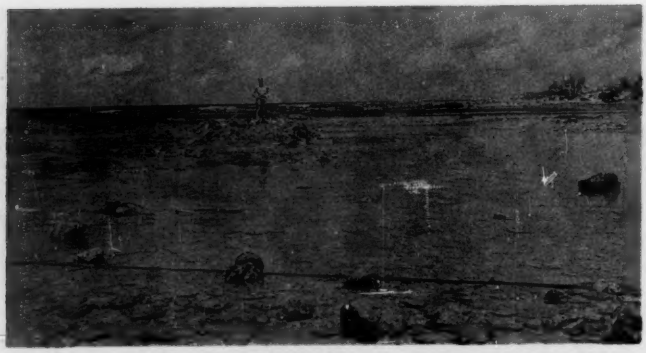

FIGURE 1. POOL FORMED BY COALESCING POTHOLES
Inland of the Lithothamnium ridge. Note cobbles in foreground. Photo by Naval Construction Battalion.

FIGURE 2. PINNACLED AND HONEYCOMBED LITHOTHAMNIUM RIDGE
Seaward edge of fringing reef, Eniwetok Island, at low tide. Photo by Naval Construction Battalion.

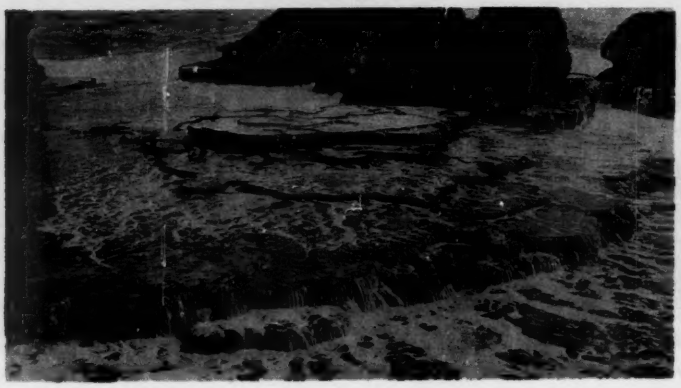

FIGURE 3. HEALTHY NULLIPORE REEF
Tongatabu Island, Tonga group. Photo by H. T. Stearns.

FRINGING REEF, ENIWETOK AND TONGATABU ISLANDS

low tide. The lagoon side of the flat is paved with cobbles and sand bound together by encrusting corals. Great quantities of debris are driven lagoonward through the channel. Branching corals are absent.

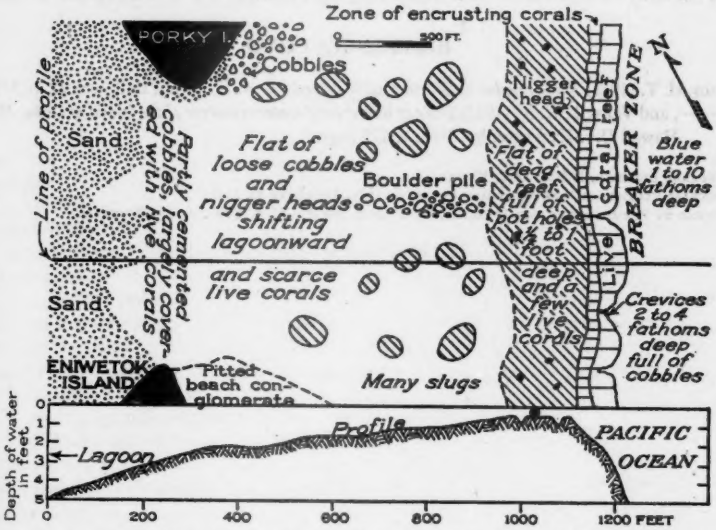

FIGURE 3.—*Plan and profile of reef between Eniwetok and Porky islands, Marshall group*

INNER REEF

Eniwetok Island is bordered on the lagoon side by beach limestone similar to that on the opposite shore, except that beds of sandy limestone are common, and the conglomerates lack boulders. The limestone has a polished surface in many places indicating abrasion by shifting beach sand. A long strip has been blasted away to obtain the underlying coral debris for construction. The limestone is 2–6 feet thick and thins toward the lagoon. Under it for an unknown depth is loose unconsolidated coquina carrying water-worn coral fragments and very little fine mud. The floor of the lagoon bordering the beach is a shelf 1000 to 1200 feet wide with less than 5 fathoms of water. The floor then drops abruptly to a narrow 10-fathom shelf and finally to 20 to 30 fathoms. A few patches of branching coral darken the otherwise aquamarine water underlain by sand between the shore and the deep blue lagoon. Specimens of fragile branching coral are scarce.

CAUSE OF DECADENCE

Little is known about the ecology of coral reefs in the western Pacific. It is unlikely that either temperature, food supply, or currents have changed sufficiently near Eniwetok Island to cause the decadence of this reef. A 5-foot drop in sea level occurred in Recent time (Stearns, 1941, p. 779), but this has not prevented the development of

healthy nullipore reefs in the Marianas, Tonga, and other island groups in the Pacific. On most islands remnants of reefs of this higher stand of the sea abound, but none have been reported from the Marshall group. Perhaps some very recent local change of level of a few feet in the Marshall Islands is the cause of the decadence.

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333 Federal Building, Honolulu 2, Hawaii

Manuscript Received by the Secretary of the Society, February 13, 1945

Published by Permission of the Director, Geological Survey, U. S. Dept. of the Interior.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 56, PP. 789-808, 3 PLS., 4 FIGS. AUGUST 1945

PUMICE BEDS AT SUMMER LAKE, OREGON

BY IRA S. ALLISON

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ABSTRACT

A section of lake beds exposed in the sides of the trench of Ana River below Ana Spring near the northwest corner of Summer Lake basin in Lake County, Oregon, reveals near the top at least six layers of pumice. Four of these appear to record eruptions of Mount Mazama which led finally to the formation of Crater Lake; the source of the fifth is not known; the sixth is attributed to a later eruption of Newberry Crater. As certain layers in the associated sediments imply shallow-water conditions, these eruptions must have occurred when the last pluvial lake, formerly about 215 feet deep, had been reduced by evaporation to a depth of about 85 feet, probably about 14,000 years ago. The data appear to extend back the ages of Mount Mazama pumice, of Crater Lake, and of Paleo-Indian occupation of the area by several thousand years.

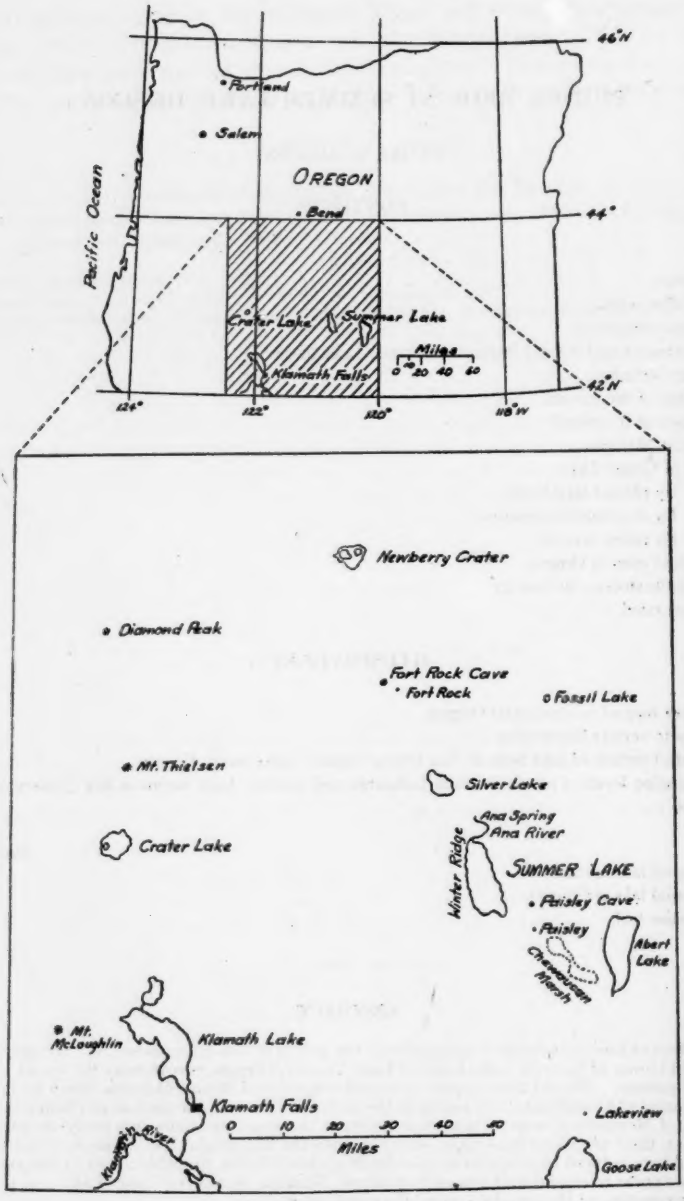


FIGURE 1.—*Index map of south-central Oregon*

INTRODUCTION

GEOLOGIC SETTING

Summer Lake basin is a well-developed fault block depression (Pl. 1, fig. 1), about 20 miles long from north to south and about 10 miles wide, situated in the northwestern part of the Basin-and-Range province in south-central Oregon (Fig. 1). The fault-line scarp of Winter Ridge on the west side of Summer Lake basin (Pl. 1, fig. 1) rises about 2000 feet within a distance of a few miles; the other boundary scarps are not so high. The geology of the region has been described by Russell (1884), Waring (1908, p. 21–31), Smith (1926), and others.

Summer Lake, a shallow alkaline lake without outlet, occupies 50 to 70 square miles of the basin, according to variations in its level from time to time. The tributary drainage area is only about 550 square miles, and the climate is semiarid; hence, no stream of any consequence enters the basin. Instead, the principal source of water for Summer Lake (more than 80 per cent according to Waring) is Ana River, which bursts forth full-grown at Ana Spring in the northwest corner of the basin, with an average flow of about 135 second-feet (Meinzer, 1927). A dam at the spring holds the water to a level of about 4225 feet above sea level (by aneroid measurement); Summer Lake is about 50 to 80 feet lower, according to its stage. On September 1, 1944, Summer Lake had an elevation of 4146.3 feet as compared with a high-water elevation of 4178 stated on maps of the U. S. Forest Service. In the first mile of its course below the dam, Ana River flows in a steep trench excavated in lake beds lying on the basin floor. The upper part of the section of lake beds thus exposed includes several layers of pumice, the interpretation of which is the special concern of this article.

These lacustrine beds not only supply a remarkably clear sedimentary record of the volcanic eruptions responsible for the pumice, but also furnish information regarding the history of a pluvial lake in its waning stages and supply data on which estimates may be made of the age of Crater Lake and of early human occupation of the area. They are, therefore, unusually significant in supplying detail for a late Pleistocene and Recent chronology.

ACKNOWLEDGMENTS

Financial assistance was furnished by the General Research Council, Oregon State System of Higher Education; pollen data were supplied by Dr. H. P. Hansen; and Dr. Howel Williams and Dr. Ernst Antevs kindly read and criticized the manuscript.

LATE PLEISTOCENE AND RECENT HISTORY OF SUMMER LAKE BASIN

A well-preserved set of shore-line features around the margin of Summer Lake basin (Fig. 2; Pl. 1) attests the former presence of deep water in the basin. The highest shore line, presumably of Bonneville age, is approximately 4500 feet above sea level[1], or about 355 feet above the present level of Summer Lake; other shore lines lie

[1] U. S. Coast and Geodetic Survey Benchmark X 72, elevation 4496.740 feet (second-order leveling), 3.2 miles north of Summer Lake P. O., is set on an outcrop of solid rock in the midst of wave-worn cobbles. Rounded stones in decreasing numbers and sizes extend up the gentle slope to the east and northeast to an elevation of about 4502 feet.

at intermediate levels. One of these, about a mile north of Ana Spring dam, has the form of a bay-mouth gravel bar at an elevation of about 4360 feet above sea level; gravel extends a quarter of a mile down its faintly ribbed southern face to about 4275

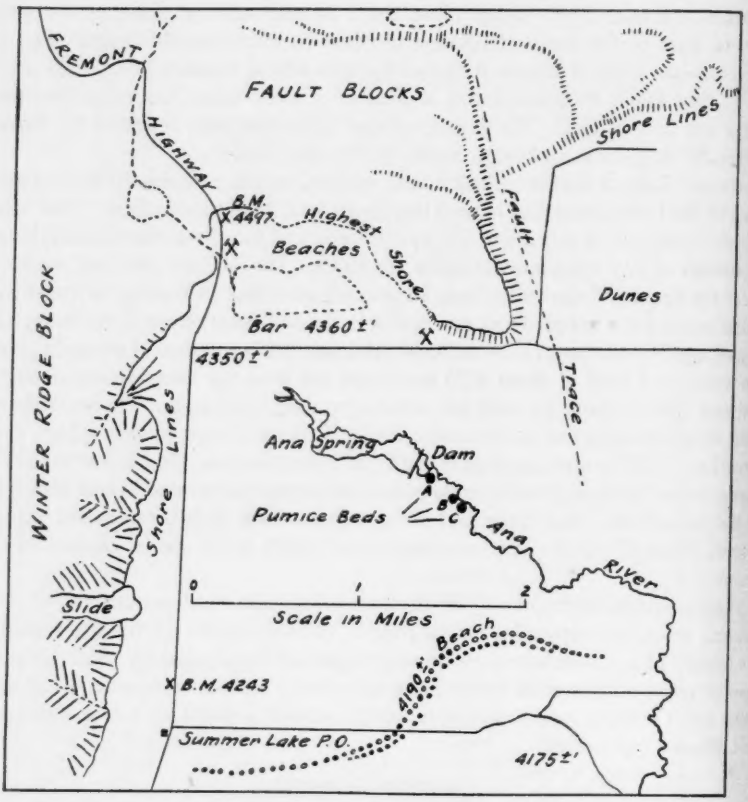


FIGURE 2.—*Key to aerial photographs*

Reproduced from vertical photographs of Soil Conservation Service, U. S. Dept. Agriculture.

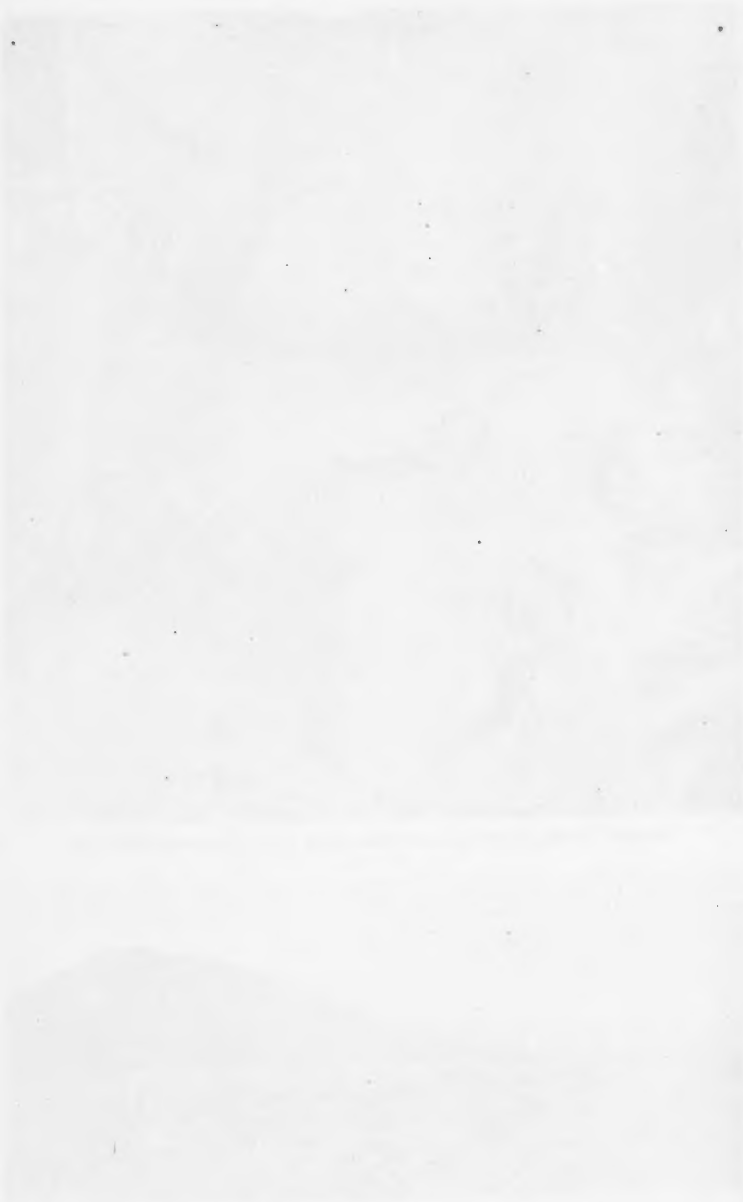
feet above sea level, where it gives way to sand on the gentle slope at the edge of the lake plain. This well-developed shore line is probably of Provo age.

At its highest stages, this deep lake extended through a gap at the southeast corner of Summer Lake basin so as to cover with about 200 to 250 feet of water (Pl. 1, fig. 2) the present sites of Upper and Lower Chewaucan marshes and Abert Lake, which are situated in similar interconnected fault troughs. The Summer Lake-Chewaucan Marsh portion of the former hook-shaped lake was about 45 miles long in the northwest-southeast direction; the fork in the Abert Lake basin, reaching northward 15 miles or more, joined the main lobe near its southeastern end. The writer calls this

FIGURE 1. AERIAL PHOTOGRAPHS OF NORTHWEST PART OF SUMMER LAKE BASIN

FIGURE 2. SHORE LINES OF BONNEVILLE AND PROVO AGES, CHEWAUCAN NARROWS

PLUVIAL LAKE FEATURES



former large, deep lake of the Bonneville stage pluvial Lake Chewaucan and the pluvial lake of the Provo stage, also without outlet, Winter Lake.

Such lakes are thought to require for their existence a cooler and moister climate than the present; accordingly, their age is presumably Pleistocene or Pluvial. A direct relation of the expanded lakes of the Great Basin to glacial stages was recognized by Gilbert (1890) and Russell (1885; 1889) and accepted later by Meinzer (1922), Antevs (1925; 1941a, p. 40), Blackwelder (1931a; 1931b; 1941; Blackwelder and Ellsworth, 1936), and others. On the other hand, the extreme recency of Lake Lahontan has been advocated by Jones (1925; 1928), but refuted by Antevs (1944).

Most workers agree that the high-water stages of these pluvial lakes were coincident with or only slightly later than the maximum stages of the Pleistocene glaciers in the mountains of the western United States and of the ice sheets in the North. The sequence of glacial stages in the Sierra Nevada of California according to Blackwelder (1931b) is as follows: (1) McGee, (2) Sherwin, (3) Tahoe, and (4) Tioga. The stages in Yosemite Valley, California, according to Matthes (1930) are Glacier Point, El Portal, and Wisconsin (with two maxima). In the Cascade Range of Oregon, Thayer (1939) found three glacial stages, which he named Mill City, Detroit, and Tunnel Creek stages, and tentatively correlated with the Sherwin, Tahoe, and Tioga stages of California, respectively.

The time relations between glaciers and lakes in the Mono Lake area on the east side of the Sierra Nevada of California, where according to Russell (1889, p. 369–371; 1885, p. 267; *cf.* Gilbert, 1890, p. 311–314) and later observers shore lines were cut on the inner as well as the outer sides of the moraines and high-level deltas were built between the morainal embankments, are summarized by Russell (1889, p. 371; *cf.* Blackwelder, 1933) as follows:

> "The two best defined advances of the Sierra Nevada glaciers and the two high water stages of the Quaternary lake of Mono Valley are believed to correspond in time with the two high water stages of Lakes Bonneville and Lahontan."

Antevs (1941b) correlates the highest stages of lakes Bonneville and Lahontan (the Bonneville Pluvial) with the Iowan-Tahoe glacial stage, and the Provo shore line in Bonneville basin and the Dendritic terrace in Lahontan basin with the Mankato-Tioga glacial stage.

Similarly the highest levels of pluvial Lake Chewaucan in Oregon probably were attained during or shortly after the Tahoe (Iowan or early Wisconsin) glacial stage of the Sierra Nevada, and some of the lower beach levels during or shortly after the weaker Tioga (Mankato or late Wisconsin) stage. The agreement of this sequence with the known history of Lake Lahontan (Fig. 4) tends to confirm these inferences.

No evidence of earlier lakes corresponding to Middle or Early Pleistocene glacial stages has been detected in the Summer Lake basin, but soft, blue lake muds are reported by Mr. Carl E. Williams, driller, Lakeview, Oregon, to have been penetrated to depths of as much as 960 and 1286 feet in unsuccessful attempts to obtain artesian water, and such great thicknesses of fine sediments seem to imply a long history.

The moderate salinity of Summer and other lakes in the Great Basin (Van Winkle, 1914; Gale, 1915) has been interpreted to signify that the present lakes are not direct

remnants of pluvial lakes like Lake Chewaucan or Winter Lake, but are only about 4000 years old. The earlier lakes must have evaporated during the dry period that prevailed some 8000 to 4000 years ago (Antevs, 1938; 1941a, p. 39), and their salts were thought to have been buried or blown out of the basins by deflation (Gilbert, 1881; Russell, 1884, p. 462; 1885, p. 224–230).

In the arid southwestern United States, a return to a wetter climate during the first half of Late Postpluvial time of Antevs' time scale, between about 4000 and 2000 years ago, is indicated (Antevs, 1941a, p. 38–42). An abandoned sandy beach ridge, standing at 4190 feet, or about 10 or 20 feet above the highest water levels of Summer Lake (Fig. 2) and formed during an expanded stage of Summer Lake, probably was coincident with just such a moist climate in this area also. It may have been formed, then, a few thousand years ago. It is perhaps noteworthy that this beach appears to truncate nearly north-south dune ridges, which in turn seem referable to the dry stage of a few thousand years previous. Relatively drier conditions, prevailing since this beach was formed, have reduced the lake to its present size. The history is summarized diagrammatically in Figure 4.

ANA RIVER SECTIONS

At Site A near Ana Spring (Fig. 2) downcutting by Ana River has exposed a 48-foot section of lake sediments that record at least the later part of the history of the pluvial lakes. About 40 feet of such sediments is revealed in a cliff beside Ana River, about 0.1 mile southeast of the dam at Ana Spring (Pl. 2, fig. 1). The lowest 12 feet consists mainly of silt, with sand at river level, and water-bearing pumice sand bed appearing again about a third of the distance up the section.

The middle portion of the section consists mainly of silty mud interbedded with thin layers of sand, ostracod shells, volcanic ash, and marl. The mud contains abundant ostracod shells or their fragments. Most of it probably accumulated in deep water, but the layers of sand are thought to indicate stages of shallow water. The marl, in two hard white layers half an inch and a quarter of an inch thick, respectively, is presumably of chemical origin, possibly a result of evaporation. An uneven or wavy contact between one mud layer and an overlying bed of sand (in the cliff at the dark line at upper left in Figure 1 of Plate 2) appears to mark a disconformity and to suggest an interval of exposure of this part of the former lake bottom during interpluvial time before the lake rose again and sedimentation was resumed. For the low-level lake of interpluvial age thus recorded in the banks of Ana River, the name Ana Lake is here proposed.

The upper third of the section likewise consists of clays and silts, with occasional layers of oölite, ostracod shells, and sand. In this part of the section, about 31 feet above the river, is a 4-inch layer of dark-brown volcanic ash that is a useful stratigraphic marker.

As the uppermost beds are lacking near the dam, or exposed only in slip blocks of uncertain position, the section is continued at Site B on the river bank, about 0.3 mile southeast of the dam (Pl. 2, fig. 2). Removal with the aid of a shovel of the surficial materials on the slope to a vertical depth of 15½ feet exposes the 4-inch layer

FIGURE 1. SECTION BESIDE ANA RIVER, SITE A

FIGURE 2. RIVER BANK AT SITES B (RIGHT) AND C (LEFT)

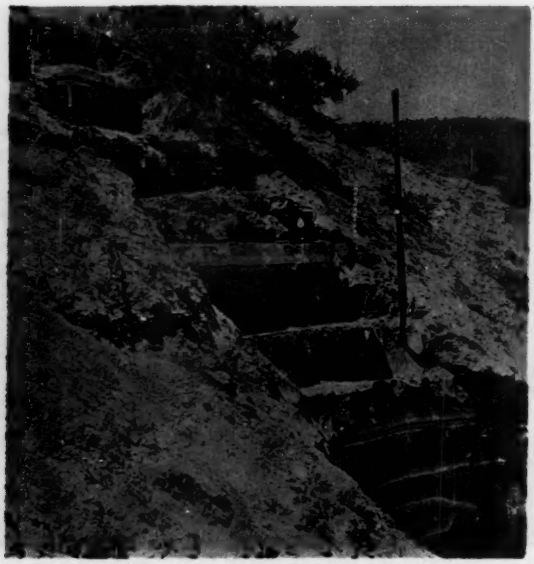


FIGURE 1. FULL SET OF PUMICE BEDS, SITE C

FIGURE 2. PARTIAL SET, SITE B

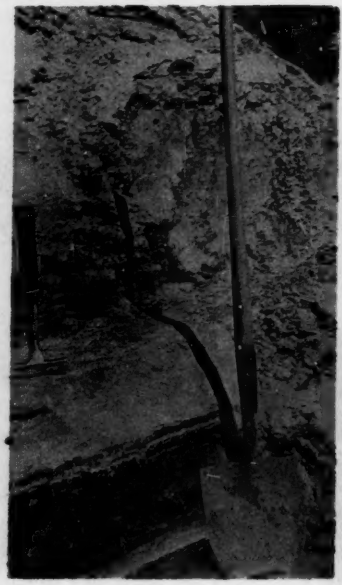


FIGURE 3. MOUNT MAZAMA PUMICE BEDS, SITE B

PUMICE BEDS

of dark-brown volcanic ash and reveals in the upper part of the section several layers of light-colored pumice or volcanic ash (Pl. 3).

Between the brown ash and the lowest layer of white pumice lies a little more than 9 feet of clay, broken into small blocks by numerous cracks caused by shrinkage during drying. In the lower part of this clay are at least five beds of an oölite-ostracod-sand mixture, one 3 inches thick and another 7 inches thick, each separated from the others by about a foot of clay, as if by some rhythm in sedimentation. The layers of pumice are described in the following section.

Another partial section, likewise obtained by clearing the slope overlooking Ana River at Site C a few hundred feet farther southeast (at the extreme left in Pl. 2, fig. 2), adds about 2 feet more to the top of the stratigraphic column. The five or more layers of light-colored pumice seen at Site B (Pl. 3, fig. 2) are exactly matched here, layer for layer, in position, thickness, and petrographic character, so there can be no doubt as to their continuity as distinct and identifiable layers. In addition, however, near the top of the section (Pl. 3, fig. 1) appears still another layer of pumice. The interpretation of these several layers of pumice is the special purpose of this article. The brown ash lower down and other much earlier layers of pumice are not considered.

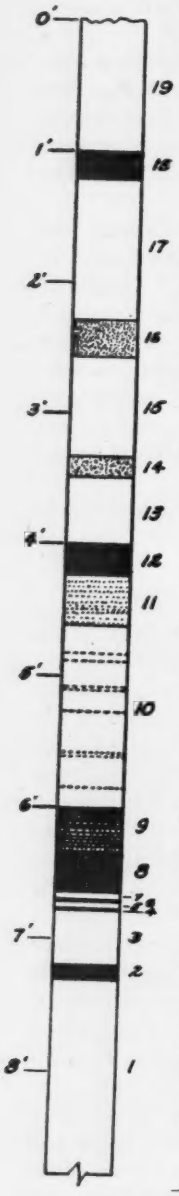
The details of the uppermost 8 feet of the section are shown in Figure 3 and in Plate 3.

DESCRIPTION OF THE PUMICE

The lowest of the six main pumice layers to be described is 1½ inches thick; of this amount, the basal ½ inch seems to represent a direct fall into the lake, whereas the remainder is laminated and shows decreasing grain size upward so as to suggest that the upper part was reworked and even washed into the lake after the eruption. In Figure 1 of Plate three, this same layer appears three times but terminates abruptly in two places; the gradation of grain in the middle position is reversed, hence there the layer is clearly upside down. The repetition and truncation of the bed probably resulted from its buckling and breaking during a minor landslide; the associated clayey silts are very slippery when wet. On account of this disturbance of the section, measurements were not carried farther down at this site. No such disturbance affects the beds at Site B (Pl. 3, figs. 2, 3).

Of the basal ½ inch, about 12 per cent ranges between ¼ and 1 millimeter in particle size, and 60 per cent is finer than a 200-mesh screen (.074-mm. opening), but in the layer as a whole more than 75 per cent is fine dust. Many of the coarse pellets of pumice are buff, and others are white. In addition to the vesicular glass, crystals of feldspar, pyroxene, and magnetite are also present but make up only about 1 per cent ot it.

The most likely source of this pumice is either Mount Mazama (on the site of Crater Lake), about 66 miles a few degrees south of west, or Newberry Volcano, 55 miles away in the direction N. 25° W. Other vents known to have ejected pumice are smaller and equally or even more distant. At such a distance a direct fall of half an inch of pumice and a total accumulation of 1½ inches in a lake basin of such limited



	Description	Thickness in inches	Depth from surface in inches
19	Soil, silt, and clay	12	0–12
18	White volcanic ash, nearly crystal-free, ascribed to Newberry Crater	2½	14½
17	Clay	13	27½
16	Sand, with hard cement in top ½ inch	3½	31
15	Clay, broken into blocks by numerous shrinkage joints	9	40
14	Sand, containing granules and small pebbles of basalt; partly cemented	2	42
13	Silt	6	48
12	White pumice, including flakes of biotite, source unknown	4	52
11	Alternating sands and silts	5	57
10	Silts with occasional thin seams of sand	15	72
9	Thin-bedded fine pumice sands with seams of fine ash	4	76
8	Coarse, crystal-rich, white to gray pumice sands, from climactic eruptions of Mount Mazama	4	80
7	Silt	½	80½
6	Volcanic ash	¼	80¾
5	Silt	¼	81
4	Fine volcanic ash	¼	81¼
3	Clay	5¼	86½
2	Volcanic ash, probably from Mount Mazama	1½	88
1	Clayey silt, blocky when dry; includes occasional layers of oölite, ostracod shells, and some sand; extends downward 9 feet or more	—	—

FIGURE 3.—*Partial section of lake beds at Ana River, Summer Lake basin, Oregon*

tributary drainage area must be the products of just such a major eruption as one might expect from Mount Mazama or Newberry Crater.

The pumice of this layer is very much like the known products of Mount Mazama, especially in its crystals. Partly for this reason but mostly for its relation to the succeeding pumice falls, it is referred to an early outburst in the late history of Mount Mazama.

The second fall consists of fine ash only ¼ inch thick; a third, also ¼ inch thick, is separated from it by about ¼ inch of silt and overlain by another silt layer ½ inch thick. These minor layers of ash appear also to represent preliminary puffs, at intervals probably of many years, preceding the maximum eruptions of Mount Mazama.

The fourth volcanic layer, or set of layers, is about 4 inches thick, its lower half light-colored and its upper half so rich in crystals of plagioclase and hypersthene as to be gray; it is apparently the product mainly of two closely timed eruptions. Two faint seams at the base, barely distinguishable in Plate 3, probably record separate outbursts at the beginning of the main eruptions.

In the basal 2 inches of the earlier part more than 50 per cent consists of particles ¼ to ½ mm. in diameter, and about half the material by weight is composed of crystals. In the main gray sandy phase more than 30 per cent falls in that size range, and as much as a fourth to a third of it consists of crystals, mostly between ¼ and ½ mm. in diameter. Plagioclase is two to three times as abundant as hypersthene and augite. This relatively high concentration of crystals may be the result of partial sorting, as by a "sink-and-float" differential between the crystals and the lighter, highly vesicular glass, as the floating of pumice until it becomes water-logged is well known[2]. A high percentage of fines (about 98 per cent) in the ash between these two sandy portions, and their somewhat different character are evidence of two eruptions, separated by a time of relative quiet.

This pumice is so distinct petrographically that its correlation with the great field of crystal-rich dacite pumice east and northeast of Crater Lake (Moore, 1934; Williams, 1942) is most fitting. Of all the pumice layers in the lake beds, it is the thickest, coarsest, and richest in crystals, just as the Crater Lake pumice is the coarsest, most voluminous, most widespread, and richest in crystals of all pumice deposits in the region. The minerals are identical and in similar proportions.

Immediately above this sandy pumice is 3½ or 4 inches of parallel-bedded pumice sands and silts (immediately below the hammer in Pl. 3, fig. 3) of approximately the same composition but of smaller grain size. Of the laminated ash at the top more than 90 per cent passes through a 200-mesh screen (.074 mm.). These finer materials at the top may have come from additional explosions of Mount Mazama or, more simply, from reworking of material that originally fell outside of but adjacent to the lake.

These pumice sands and silts give way to about 15 inches of silts in the midst of which appear several thin seams of sand (Pl. 3, fig. 1), including grains of basalt (the

[2] Concentration of pebble pumice took place on beaches in the Fort Rock basin farther north. Possibly a careful search of the Summer Lake basin might reveal similar, though sandy, beaches and hence establish more accurately the approximate levels of pluvial Winter Lake at the times of the several eruptions considered here.

main local rock), and these silts in turn are overlain by 5 inches of alternating sands and silts. The change in sedimentation from the previous clayey silts to coarser materials of local origin suggests shoaling of the lake, presumably by evaporation, but with many minor oscillations of level, and the incorporation of materials derived from near-by shores.

The fifth layer of pumice is 4 inches thick, its basal ½ inch sandy and characterized by spangles of dark mica, the next ¾ inch fine-textured and white, and its upper part (about two-thirds of the total) thinly laminated and slightly grayish. The difference in color is evident in Figure 1 of Plate 3. The bottom part, 1¼ inches thick, unbroken by bedding planes, probably is the result of pumice falling directly into the lake. The upper part is probably secondary and grayish from impurities of mud. The curve of distribution of grain sizes in the lower part shows two high points (as does most of the local pumice), one in the range between ⅛ and ¼ mm., and the other less than .074 mm. Of the material in the basal ½ inch almost half ranges between ⅛ and ¼ mm. in diameter. Of the upper part about 90 per cent is finer than .074 mm.

This pumice has a low index of refraction and, therefore, probably is silicic. It includes crystals of hornblende and numerous flakes or scales of dark-green or brown biotite. These biotite flakes are highly characteristic, even diagnostic, of this layer and have not been found in any of the others. Biotitic pumice crops out at the "county bridge" across Ana River, about 2 miles southeast of Ana Springs dam, and the writer also found a small patch of it in the wind-eroded area east ot the middle of Summer Lake several miles farther south. Similar flakes of biotite reported by Dole (1941; unpublished thesis) in sediments near Fossil Lake, about 25 miles northeast of Ana Spring, are thought to be correlative. At Fossil Lake biotite first appears in a 6-inch layer of pumice in the lake beds and continues in the overlying sandy beds as well as in Recent dune sands derived therefrom. The exact source of this biotite pumice is not yet known, but as the initial layer is thicker at Fossil Lake than at Summer Lake it presumably came from some vent in the Newberry area, perhaps from one of several subsidiary cones.

Between the fifth and sixth layers of pumice are beds of silt and clay, interrupted by 2-inch and 3-inch layers of sand. These sands, and especially the granules and small pebbles of basalt in one of them, clearly indicate shallow-water conditions or storm waves at the time of their deposition.

The sixth and last layer of pumice, 2½ inches thick and white, is composed almost entirely of particles of glass in which crystals are generally sparse, although the basal half inch contains about 2½ per cent magnetite, hypersthene, and augite, and nearly 4 per cent feldspar. Thus, it differs considerably from the earlier pumice and closely resembles the silky pebble pumice low in crystal content found in the vicinity of Newberry Crater and in the lake beds and beaches in the Fort Rock-Christmas Lake-Fossil Lake basin between Newberry Crater and the site of this section. Thus its correlation with the climactic outburst of Newberry Volcano (Williams, 1935) is suggested. Although pumice of Newberry origin occurs as pebbles in the Fort Rock basin to the north, the material here is relatively fine-grained; about 75 to 80 per cent of it is less than .074 mm. in diameter.

At the edge of the steep slope overlooking Ana River at Site C, only about 1 foot of material overlies the uppermost pumice layer. Probably 3 or 4 feet of cover,

partly windblown, occurs immediately beneath the surface of the lake plain generally, but the pumice layer lies almost at the brink of the rim, and there is only a very slight increase in elevation farther back. For lack of time no pits were dug to verify its

TABLE 1.—*Summary description of pumice layers near Ana Spring, Oregon*

Sample No.	Apparent Source	Percentile distribution of grain sizes (in mm.)							Distribution by Weight		
		Over 1	1–½	½–¼	¼–⅛	⅛–.074	.074–.104	Under .074	Heavy Sp. gr. > 2.87	Medium Sp. gr. 2.87 to 2.60	Light Sp. gr. <2.60
	Newberry Crater										
43-104		—	.14	.75	15.83	6.09	4.17	73.02	.38	.35	99.27
43-91		.09	.37	3.83	11.94	3.17	2.87	77.73	.78	.56	98.66
43-55		.22	.31	1.43	14.29	3.59	2.98	77.18	.78	1.50	97.72
43-53		—	.21	2.24	12.46	4.04	2.78	78.27	.80	1.66	97.54
43-89b	second ½ inch	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	98.17	.32	.10	99.58
43-89a	basal ½ inch	—	.71	4.27	49.05	12.70	7.30	25.97	2.44	3.70	93.86
	Not known										
42-16	whole	—	.02	.65	9.37	5.74	10.67	73.55	1.08	6.82	92.10
43-52	whole	—	.02	.81	10.84	7.36	12.92	68.05	1.34	10.12	88.54
43-100	upper part	.18	.01	.02	.33	.44	1.85	97.17	—	.21	99.79
43-99	basal 1½ inches	—	.11	1.42	28.60	14.72	19.31	35.84	8.16	7.78	84.06
	Mount Mazama										
	Climactic eruption:										
43-97	laminated upper part	.01	.10	.56	1.55	.78	2.66	94.34	.18	.23	99.59
43-51	middle gray sandy phase	2.12	17.25	34.96	16.79	.55	.79	26.02	9.28	27.68	63.04
43-96	middle gray sandy phase	1.12	11.29	38.68	18.14	.54	.66	29.57	10.16	13.62	76.21
43-87	middle gray sandy phase	.30	8.30	29.86	32.61	2.26	3.77	22.90	8.12	29.50	62.38
43-86	next ½ inch	—	.01	.10	.72	.30	.60	98.27	.50	.20	99.30
43-85	basal 2 inches	1.70	16.74	52.46	23.29	.36	.41	5.04	17.92	38.32	43.76
	Early eruption:										
43-94	whole	.03	.79	2.46	8.46	4.44	7.28	76.54	.14	.04	99.82
43-84	basal ½ inch	56	4.56	7.00	11.76	5.01	10.80	60.31	.74	.60	98.66

depth elsewhere. The surface of the lake plain bears scattered low bushes of greasewood and rabbit brush and is uneven to the extent of a foot or two as a result of the work of the wind in shifting loose material between or about the bushes. Of the material lying above the uppermost pumice layer about 97 per cent is finer than 200 mesh (.074 mm.). It includes volcanic ash and may have been derived by reworking pumice from adjacent areas before pluvial Winter Lake finally left the site.

In Table 1 the textures and other characteristics of the several layers of pumice are compared. The distribution of particles according to their specific gravity is approximate only, as separations in bromoform are imperfect because glass adheres

to the crystals even after grinding; however, notwithstanding this difficulty, it furnishes a rough measure of the relative amounts of (1) ferromagnesian minerals and magnetite, (2) feldspar, and (3) glass. The abundance of feldspar and pyroxene in the climactic pumice fall from Mount Mazama is striking. In the biotitic pumice, however, flakes of mica range through both heavy and medium-weight fractions, and no simple interpretation of the figures presented is possible.

SIGNIFICANCE OF THE RECORD

MOUNT MAZAMA

The several layers of pumice attributed to Mount Mazama amplify the record of eruptions discerned by Williams from the subaerial deposits near Crater Lake. The record in general confirms his statement (1942, p. 71) concerning the pumice "that the whole eruptive episode was short-lived and that the explosions, if not actually continuous, followed each other at short intervals," although this lacustrine record, including the preliminary ash falls, implies a lapse of time probably to be measured in many years between the several successive outbursts that culminated in the great voluminous falls and flows of crystal-rich pumice. The interval between the first and second outbreaks was long enough for about 5 inches of mud to accumulate in a lake basin of very limited tributary area—perhaps several decades or even a few centuries. The next eruptions probably followed at intervals of decades or less. Thus these lake beds corroborate Williams' work and supply additional detail, especially concerning the several preliminary outbursts and the double character of the climax.

AGE OF CRATER LAKE

By pluvial lake levels.—A corollary from the lacustrine record of these pumice falls is that the eruptions, not only of Mount Mazama but also of Newberry Crater, took place while the northwestern part of Summer Lake basin (some 80 feet above Summer Lake in 1944) was still occupied by the pluvial Winter Lake. Part of the associated sediments clearly imply shallow water. Although Winter Lake once had been about 135 feet deep over the site, by the time the pumice falls occurred the lake level had declined to a local depth of only a few feet, or perhaps 20 feet at most, or probably to a level of about 80 to 100 feet above the present level of Summer Lake. Continued evaporation stopped subaqueous sedimentation at the site not long after the Newberry pumice fall was incorporated in the lake sediments.

The fact that the pluvial lakes were still in existence at the time of the several pumice falls, including that of Newberry, had been discovered earlier by the writer in studies of the lake sediments in the Fort Rock basin to the north, and it was the search for a clean-cut record of these relations that led to the investigation of this section along Ana River in Summer Lake basin.

Can the record be interpreted in terms of years? If, following Antevs (1941a, p. 42; personal communication, 1944), we assume that the climax of the last glacial stage was reached 25,000 years ago, the last high pluvial lake stage may have been reached some 23,000 years ago. Antevs thinks that the several pluvial lakes may

have persisted until 10,000 years ago, by which time the climate gradually had returned to "normal." Some geologists and climatologists may consider this lag too long; probably few would think it too short, as stratigraphic and pollen analyses of peat deposits and other evidence from unrelated fields of research indicate a relatively dry, warm climate between 8000 and 4000 years ago (Sernander, 1911; von Post,

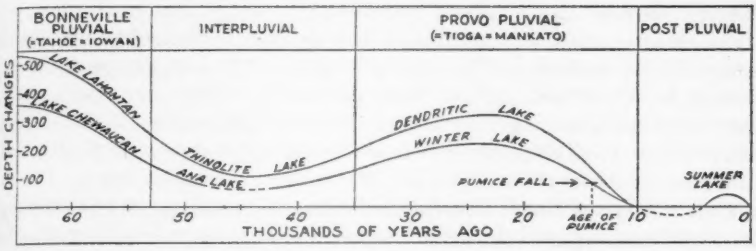


FIGURE 4.—*Changing levels of pluvial lakes in Lahontan and Summer Lake basins in late Quaternary time*

The upper curve shows the changing levels of Lake Lahontan, Thinolite Lake, and Dendritic Lake in relation to modern Pyramid Lake in Nevada (after Antevs). The lower curve represents the corresponding changes in depth of Lake Chewaucan, Ana Lake (exact level not yet known), Winter Lake, and Summer Lake, Oregon, in comparison with the present Summer Lake, and hence indirectly reflects the climatic history of the region during the past 65,000 years. The inferred depth of pluvial Winter Lake at the time of the pumice falls is used to date the age of the pumice—according to the chart about 14,000 years.

1930; Antevs, 1938; Hansen, 1938; 1944; Matthes, 1939; 1940; Sears, 1941; 1942; Cooper, 1942; Cressman, 1940; Deevey, 1944).

The changing levels of the pluvial lakes in Lake Lahontan basin, Nevada, and in Summer Lake basin, Oregon, are plotted in Figure 4. The time scale, the general form of the graph, and the data on Lake Lahontan were kindly supplied by Antevs. The curves are drawn as smooth lines, but the probable occurrence of temporary standstills and even of minor oscillations or reversals of the prevailing trends should be kept in mind. On the assumption that Winter Lake of the Provo pluvial stage 23,000 years ago stood about 215 feet higher than Summer Lake (as of 1944) and progressively had been reduced by evaporation to the equivalent of modern Summer Lake 10,000 years ago, the depth corresponding to that existing at the time of the pumice fall should have been reached about 14,000 years ago.[3] An estimate of 14,000 years for the age of Crater Lake, therefore, is suggested. This nearly trebles the estimate of about 5000 years (4000 minimum, to 7000, maximum) made by Williams (1942, p. 112–114).

By stratigraphic position.—Another method of estimating the ages of the pumice layers is based upon their stratigraphic position relative to the supposed disconformity shown in Figure 1 of Plate 2. If one eliminates from consideration the materials that probably accumulated at the most variable and generally rapid rates, such as

[3] A variety of curves may be drawn between the two points on the time scale, and their forms may be altered further by changing the ratio of the horizontal to the vertical scale. The apparent age of the pumice on several alternative graphs ranges from about 11,500 years to about 16,000 years, according to one's assumptions concerning the time and the rate of decline of the lake levels. Other modifications result from changes of the assumed dates. The curve of Figure 4 is intermediate in form, but its limitations in precision are recognized.

the layers of ostracod shells, oölite, and sand that occur in the lower levels, and the layers of pumice, silt, and sand in the upper levels, the remainder of the section above the disconformity consists of about 16 feet of fine-grained matter whose rate of deposition presumably was slow and perhaps more or less uniform. This fine-grained stuff makes up the bulk of the section; unfortunately, it is not varved. Of these 16 feet, about five-sixths lies below and one-sixth above the first layer of pumice attributed to Mount Mazama.

If we assume further that lacustrine sedimentation was resumed at that disconformity near the beginning of Tioga glacial stage when the lake was again about 70 feet deep, say 43,000 years ago, and continued until say 10,000 years ago, a span of about 33,000 years, the proportional division of time would be about 27,500 and 5500 years respectively. This corresponds to an average rate of deposition of silts, clays, and organic matter of about 1 foot per 2000 years—a reasonable figure. On that basis, the first layer of Mount Mazama pumice described herein would be a little more than 14,000 years old, and the age of the main Crater Lake pumice layer would be about 500 years less than that. Similarly estimated, the eruption of Newberry pumice took place about 3000 years later, or about 10,500 years ago, not far from the figure assumed for the end of glaciopluvial time. A change of that assumed figure of 10,000 years by 1000 years either way would increase or decrease the calculated times proportionately.

The actual rate of sedimentation is not known, and as this method of estimation involves several assumptions, particularly as to the date of the disconformity and the exact duration of the last pluvial stage, its reliability may be questioned; nevertheless, with due recognition of its defects, it may still show the general order of magnitude of the time involved—certainly many centuries, and perhaps a few millennia between the early eruptions of Mount Mazama and the eruption of Newberry Crater.

By pollen records.—Generally confirmatory evidence of the age of the pumice is furnished by certain deposits of peat. On the basis of the thickness of peat overlying Mount Mazama pumice, Hansen (1942a, p. 533) estimated the time of the eruption to be between 5000 and 7500 years ago. Examination of his data concerning the pollen in a bog near Williamette Pass, where crystal-rich Mount Mazama pumice occurs at a depth of 2.5 meters in a deposit of peat 2.75 meters thick, shows an increase of lodgepole pine (*Pinus contorta*) and decrease of western white pine (*P. monticola*) or of white bark pine (*P. albicaulis*) from the bottom upward to the 2.25-meter level, followed by an increase of Douglas fir (*Pseudotsuga taxifolia*), Engelmann spruce (*Picea engelmanni*), and western hemlock (*Tsuga heterophylla*) from 2.25 meters to the surface. Notwithstanding the effects of pumice and the great increase of dominant lodgepole pine resulting therefrom, which tend to mask effects of climate, the pollen changes in the lowest levels apparently indicate a progressive change toward a warm and dry climate that reached its maximum development at a depth of 2.25 meters, and a prompt return to a moister climate thereafter. The upper 2.25 meters of peat is fibrous and accumulated relatively rapidly, whereas that near the base is limnic and undoubtedly accumulated very slowly. The uppermost 2 meters may be equivalent to about 4000 years, and the whole deposit perhaps two to four times as much. In the absence of greater detail concerning the basal peat which encloses

the Mount Mazama pumice, it does not seem feasible to attempt an estimate of the age of the peat enclosing the pumice, except to note that the pumice was distributed prior to the culmination of the dry climate, and hence more than 6000 years ago.

A better basis for an estimate is provided by the peat and other pollen-bearing sediments in Tumalo Lake (Hansen, 1942b) near Bend, Oregeon, where in a section of peat 7 meters thick two layers of pumice are present at depths of 2.0 and 4.5 meters respectively. Although, judging by the depths, Hansen thought the upper pumice probably came from Mount Mazama, the present writer has identified the lower, finer one unmistakably as the crystal-rich pumice of Mount Mazama. The other layer includes pieces of pumice as much as 6 millimeters in diameter, bits of obsidian, and a few crystals of feldspar and is unlike any known pumice from Mount Mazama. It presumably came from some nearer volcano, perhaps South Sister or Devil's Hill (Williams, 1944, p. 57–58).

According to Hansen, early postglacial predominance of larch recorded in this bog gave way to lodgepole pine, and this in turn to western yellow pine, as the climate became warmer and drier during early postglacial time. The eruption of pumice, buried at a depth of 4.5 meters, and now known to be from Mount Mazama, caused an abrupt increase in lodgepole pine (the principal tree living on the pumice field today) at the expense of western yellow pine. The present writer interprets the subsequent increase of western yellow pine and decrease of lodgepole pine, especially between the depths of 3.5 and 2.0 meters, and a later reversal of this trend, reaching another maximum for lodgepole pine at a depth of 0.75 meter, to indicate changes of climate—first to a warm, dry climate, and later to a cooler, wetter one. If, on that basis, the peat at a depth of 2.75 meters be assigned an age of 6000 years (the supposed maximum of dry climate), the Mount Mazama pumice at a depth of 4.5 meters would be of the order of 10,000 years old. As the bog was ponded by a moraine in a short valley with limited snow-gathering area, where it seems unlikely that a glacier would have persisted later than 15,000 to 18,000 years ago, the lowest 2 meters of limnic peat may be allotted an additional 5000 to 8000 years. Or, if the age of the bog be taken as 15,000 to 18,000 years, and a conservative time differential of only two to three in the rate of accumulation be allowed the upper peat as compared with the lower peat, the lower peat would have required 6000 to 7200 years and the upper peat 9000 to 10,800 years, respectively. By either method of calculation, then, the Mount Mazama pumice appears to be about 10,000 years old.

Unpublished data on pollen from two bogs in Rogue River valley, which overlie the latest pumice from Mount Mazama and contain only moderate amounts of pollen of lodgepole pine (and hence relatively free from its masking effect), indicate similar expansion of western yellow pine and the occurrence of a dry period after the eruption of Mount Mazama (Hansen, 1944) and thus tend to confirm the earlier date here assigned to the eruptions.

Thus we have three answers concerning the age of the main sheet of Mount Mazama pumice and of Crater Lake: (1) about 14,000 years, based on climatic conditions necessary for the persistence of pluvial lakes; (2) about 13,500 years, based on the rate of sedimentation; (3) 10,000 years, based on peat profiles. As the first two nearly agree, whereas rates of peat accumulation differ and generally are

less reliable, the estimate of about 14,000 years for the age of Crater Lake is preferred.

ANCIENT MAN IN OREGON

Inasmuch as obsidian knives were found at the Wikiup site on the Deschutes River near Bend, Oregon, in material underneath the pumice from Mount Mazama (Cressman, 1937), these artifacts also appear to be more than 14,000 years old, somewhat older than previous evidence has indicated. If the Paleo-Indians lived there before the pumice fall, which in turn took place a few millennia before Winter Lake had disappeared from the Summer Lake basin, the Paleo-Indians must have been present during the waning stages of that lake. This accords with Antevs' estimate (1935) that man first "reached the Southwest at the transition between the pluvial and the postpluvial epochs, or roughly 12,000 years ago," and his later conclusion (1937, p. 48) that the artifacts associated with the overflow levels of pluvial Lake Mohave may be at least 15,000 years old.

Pumice from Mount Mazama also overlies human artifacts in caves near Paisley (Cressman and Williams, 1940) that were excavated about 60,000–65,000 years ago by waves on the shore of pluvial Lake Chewaucan. If, as now seems highly plausible from the evidence at the Wikiup site, the Paleo-Indians were present in the region during the late stages of pluvial Winter Lake, the Paisley caves must have been occupied about 14,000 years or more ago also.

As the Paisley caves are now situated about 5 miles from fresh water, provision of a water supply for the cave dwellers has seemed a difficulty heretofore, but the continued existence of pluvial Winter Lake near the caves during the stages of human occupation greatly simplifies that problem. The continuation of a pluvial climate for a long time after the high-water stages of Lake Chewaucan and Winter Lake also helps to explain the presence of horse, camel, bison, wolf, fox, aquatic birds, etc., found in one of the caves by Cressman (1939), in association with signs of human occupation.

Three samples of Mount Mazama (or Crater Lake) pumice taken from the Paisley caves by the writer showed the principal grain size to be $\frac{1}{4}$ to $\frac{1}{2}$ millimeter in diameter, somewhat finer and bearing more crystals than those analyzed by Williams. As the pumice in the caves is clearly air-laid and in places 18 to 24 inches thick (Cressman, 1940, p. 301; 1939, p. 172), whereas the corresponding water-laid material on the lake bed, as reported herein, is only a few inches thick, some special method of accumulation to that exceptional thickness is required. As a complete review of the problem would extend beyond the limits of this article, a summary must suffice. The crux of the question is whether the pumice was blown into the caves sometime after, perhaps long after, the original pumice fall, as during the dry period of 8000 to 4000 years ago, or whether it accumulated essentially at the time of the pumice fall. The purity of the pumice, the difficulty of carrying the pumice particles from the edge of the lake plain up hill over or through a coarse boulder field to the cave entrances about 100 feet higher, the presence of notable amounts of crystals of hypersthene and plagioclase that should have been winnowed out from the lighter glass

during such traction on the ground, and the failure of the wind thus to deliver pumice to the caves recently all are evidence against secondary eolian origin.

Instead, it seems more likely that as the pumice sand fell on the fairly steep slope (30° or more) that rises about 200 feet above the caves, it tumbled, rolled, or slid down the slope, like hail from a roof, and accumulated on a narrow bench at the mouth of the caves in an amount adequate to explain the present thickness. Only minor wind action, tramping, etc., would then be needed to distribute the material within the caves. It may be noted that the width of Cave No. 1 at the edge of the projecting overhang is almost 40 feet and of the cave proper about 16 feet, as compared with a length of about 20 feet. Rainwash would have assisted in the removal of pumice from the slope, notably sparse there today (Cressman and Williams, 1940, p. 71), probably within a few years but also would tend to introduce foreign particles of basalt that seem to be few or lacking.

If the hail analogy holds, the pumice at the cave mouth is primarily a gravity deposit and not strictly eolian. A necessary condition is that the hillside at the time could not have been covered with brush or timber. Antevs (personal communication) suggests that the purity of the pumice would have been maintained and its delivery facilitated by a ground cover of firm snow at the time of the fall.

These considerations tend to stress the importance of the primary fall of pumice, to minimize the amount of eolian redistribution at the cave site, and, in view of the lacustrine record of the fall, to justify an estimate of about 14,000 years or more for the age of the underlying materials in the caves.

Similarly, if we accept the view of Williams (Cressman and Williams, 1940, p. 68, 77–78) and Cressman (1943) that a *nuées ardentes* fall of hot Newberry pumice was responsible for burning fiber sandals found under pumice in a similar cave near Fort Rock, Oregon, and reject the possibility that the pumice was merely blown into the cave later by the wind, the date of occupation of this cave is also extended back to about 10,500 years or more.

We may conclude, therefore, that the evidence from the lacustrine record of the several pumice falls in the Summer Lake basin tends to substantiate the judgment of Cressman (1942, p. 94, 135–140) concerning the antiquity of man in south-central Oregon, founded in part on cultural considerations, that the period of human occupation of the region began at least 10,000 years ago. Moreover it tends to increase that figure to some 14,000 years ago.

POST-PLEISTOCENE CHRONOLOGY

Inasmuch as certain of the layers of pumice or volcanic ash are petrographically distinct, they should be identifiable in the deposits of many postglacial lakes and peat bogs in the Cascade Range and perhaps even in thin seams near the periphery of their distribution. That such ash falls are widespread is shown by their appearance in peat samples collected by Hansen (1942b) near Bend, Oregon, in the Willamette Valley, in the Puget Sound region, in eastern Washington, in northern Idaho, and elsewhere. Systematic sampling in lake and bog deposits of the ash from various volcanoes in their overlapping ranges should assist in establishing stratigraphic markers that will dovetail into the peat and pollen profiles so as to furnish

a more satisfactory time scale for post-Pleistocene stratigraphy in the Pacific Northwest. A beginning has been made on this promising project, and the co-operation of other workers is invited.

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Manuscript Received by the Secretary of the Society, February 20, 1945.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 56, PP. 809-818, 1 PL., 2 FIGS. AUGUST 1945

SOLUTION EFFECTS ON ELEVATED LIMESTONE TERRACES

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ABSTRACT

Limestone terraces on a number of islands in the southwest Pacific show a well-developed wall or rampart along their seaward edges that apparently is formed by solution. Such rimmed terraces resemble, on a much enlarged scale, the solution facets developed on flat-lying joint blocks of limestone, recently described by Smith and Albritton (1941). In an attempt to check the interpretation of field observations, a rimmed facet was produced experimentally in the laboratory. The artificial structure appears to be very similar to the natural facets on joint blocks and in many ways closely resembles the much larger rimmed terraces of the Pacific islands. It is believed that rimmed terraces with a profile similar to that of the island of Eua, Tonga, indicate island uplift accompanied by tilting.

INTRODUCTION

Some of the numerous limestone terraces on the islands of the southwest Pacific are the result of wave erosion during relatively lower stands of the islands; others have been produced by differential erosion of the limestone and the volcanic rock on and against which the limestone rests. As seen in profile from a distance the terraces seem to be flat. Closer examination shows that this is true for some, but the surfaces of others are roughened by limestone stacks and sink holes. Some of the terraces are remarkable in that they show a well-developed wall along their seaward edges. The wall is the upward continuation of the nearly perpendicular cliffs bordering the terraces and stands like a rampart above the terrace floor. In the present

paper, terrace walls located on several Pacific islands are briefly described and their origin discussed.

ELEVATED LIMESTONE TERRACES

EUA IN TONGA

The island of Eua is located at the southern end of the Tongan group in about Lat. 21° 20′ S. and Long. 175° W. It is elongated in a north-south direction, measuring 12¼ miles in length. From a maximum width of 4½ miles near the middle it tapers to points at the two ends. A limestone ridge, known as the "ridge summit," which reaches a maximum altitude of 960 feet, extends along the eastern side of the southern half of the island for about 6 miles (Fig. 1). The eastern or windward side of the ridge is bordered with steep cliffs separated in places by well-defined terraces, so that it looks like a gigantic staircase leading from the sea to the ridge summit.

Six terraces with average altitudes of 100, 200,, 340, 400, and 550 feet can be recognized in addition to the irregular surface of the ridge summit that lies about 850 feet above sea level. A limestone wall or rampart fringes parts of the seaward edge of several of the above-mentioned surfaces. It is best developed on the 550-foot terrace and along the eastern edge of the ridge summit. It is cut in craggy, massive limestone. In some places on the ridge summit the wall is 30 feet high and 50 feet broad at its base (Pl. 1, fig. 3). In other parts of the ridge summit and on the lower terraces it may be only 3 or 4 feet high and 2 feet broad at its base, tapering upward to a jagged, serrated crest (Pl. 1, fig. 2). The sea cliffs that border the terraces may be smooth or furrowed by lapies.

TUVUTHÁ AND WANGAVA IN EASTERN FIJI

Tuvuthá in Lau, or Eastern Fiji, is located at Lat. 17° 40′ S. and Long. 178° 55′ W. It measures about 3.5 by 2 miles. Limestone cliffs encircle the island almost completely but are interrupted in several places by small patches of volcanic rock. Magnificent sea cliffs 400 to 500 feet high border the southeastern and northern sides of the island (section A-A′, Fig. 2). Cliffs are 25 to 60 feet high along the northwestern and western sides.

Two distinct terraces break the uniformity of the high cliffs, one at an altitude of about 200 feet (section A-A′, Fig. 2), the second at about 450 feet. From the inner edge of the higher terrace there is a steep rise to the high rim (Fig. 2). In most places the lower terrace is a very narrow strip between the lower cliff and the higher one farther inland. Behind the village of Tuvuthá, on the southwestern coast, the 200-foot terrace is only 250 feet wide. Farther south it is even narrower and in some places is missing.

The terraces of the western side of Tuvuthá possess the best-developed marginal walls or ramparts seen anywhere in Tonga or Fiji. Edging the seaward side of each terrace is a narrow wall 5 to 100 feet high that is an upward extension of the vertical cliff which drops to lower levels.

The floors of the terraces are fairly flat except for a few sink holes and small projecting pinnacles. Some of the pinnacles are 10 feet high and 5 or 6 feet in diameter; they differ from sea stacks or mushroom rocks in that they show no undercutting.

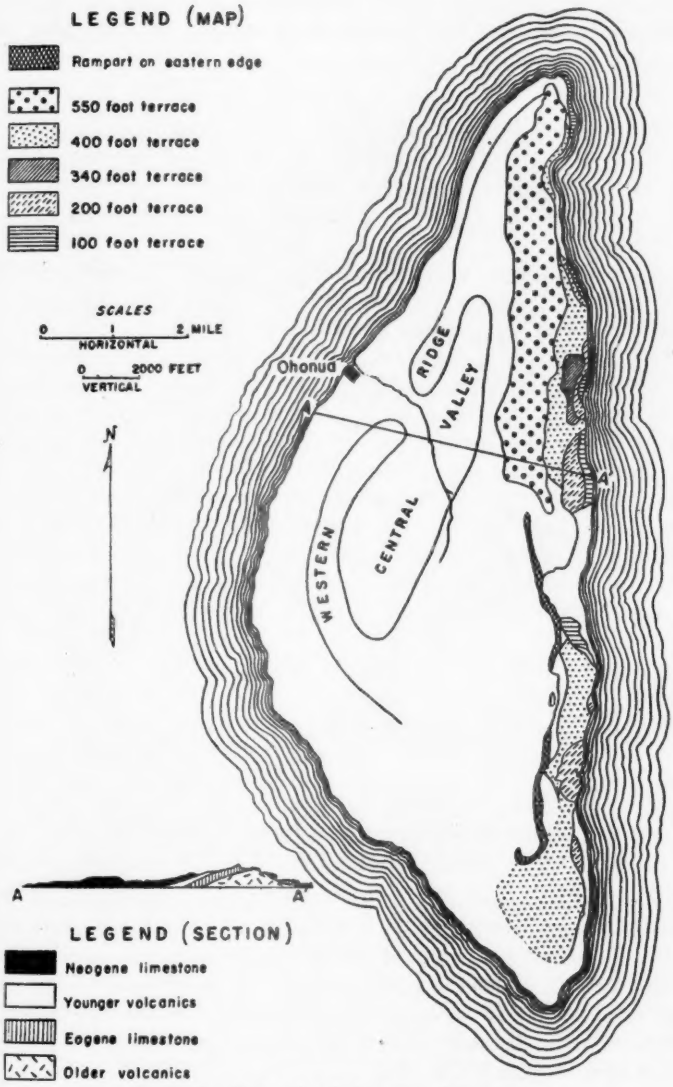

FIGURE 1.—*Map and geologic section of Eua, Tonga*
Showing eastern terraces and ridge summit; based on plane table survey

The narrower terraces are like miniature canyons edged on the outer side by the rampart and on the inner by the steep cliff leading to the next higher terrace. Each terrace is similar to the flat roof of a building with a false second story on one side.

The high rim that encircles Tuvuthá encloses three basins (Fig. 2). In the South Basin solution has removed the limestone cover, exposing the underlying volcanic foundation.

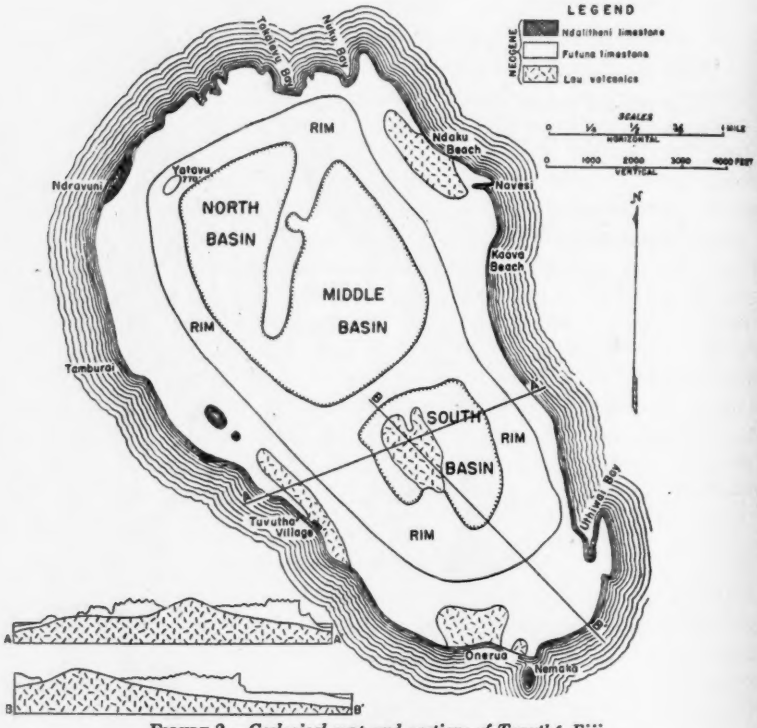

FIGURE 2.—*Geological map and sections of Tuvuthá Fiji*
Outline of island from compass-and-pace traverse

Wangava is an elongate island, about 3 miles long and 1½ miles wide, 85 miles south-southwest of Tuvuthá. It is a basinlike island whose marginal ridge of limestone rises in most places at angles of 40°–50° to an even-crested rim nearly 300 feet above sea level. In profile the northeast tip of the island appears to be distinctly terraced. The coastal flats lying only a few feet above sea level are bordered by a 15-foot rim or wall of limestone which is the lowest of three false fronts that are comparable in form to those of Tuvuthá.

These limestone walls are examples of a physiographic feature that appears to be widely developed in the Pacific islands (Hoffmeister, 1932; Ladd and Hoffmeister, 1945).

The walls bordering the terraces were formed in large part by atmospheric solution, as indicated by the serrated, knife-edged crests, the furrowed concave inner side of the wall, and the vertical, fluted seaward side. It is not clear, however, why

solution resulted in this peculiar wall-like structure, nor why walls were formed on only some terraces.

SOLUTION STRUCTURES

NATURAL FACETS ON JOINT BLOCKS

Smith and Albritton (1941) described the effects of solution on joint blocks of the Cretaceous Finlay limestone in the Sierra Blanca area of Texas. They recognized three main types of solution effects: (1) a solution pit which is shallow, subcircular, and steep-walled and is called a "tinajita"; (2) a "solution facet"; and (3) a "solution furrow."

According to the authors the type produced is determined by the original slope of the surface of the joint block. If the upper face of the block is horizontal or inclined less than 3°, a tinajita will form. If the upper surface slopes 3°–6°, solution facets will result; if 20° or more, solution furrows or lapies will be produced. Some of the larger facets studied by Smith and Albritton covered 30 square feet.

Solution facets are plane surfaces produced by corrosion. The description and illustrations of the facets on the blocks of Finlay limestone recall the wall-edged limestone terraces of the Pacific islands, for the blocks are perfect miniature replicas of the terraces. It was not so much the plane surfaces which attracted our attention but rather the irregular walls which bounded their upslope sides. At the upslope margin of each block there is an upstanding crest which is "sharp, irregular, and unsymmetrical with the upslope side nearly vertical and the downslope side concave" (Smith and Albritton, 1941, p. 69). This could be an exact description of the crested edges of the limestone terraces.

A few inches downslope from the crest of the block the concave slope merges with the slightly inclined plane surface of the block. On a much larger scale this is typical of the terraces on Eua and many other islands.

According to Smith and Albritton, solution facets are formed by meteoric water in regions of slight rainfall on joint blocks of limestone, which possess dip slopes of 3°–6° or possibly somewhat more and are surrounded by vertical sides. The water runs down the inclined surface of the block, dissolving limestone on its way, and drops into the joint gutter at the downslope end of the block. All raindrops which fall on the surface will affect the lower portion of the block. On the other hand, only those drops which fall on the upper margin of the block will dissolve the limestone of that area. This differential action causes the lower area to be etched much more than the upper portion. Eventually a sharp, crested rim will form along the upper margin, and a solution facet will develop over the remainder of the surface. Slight furrows will appear on the concave downslope side of the crest which will end when the facet area is reached. The facet remains relatively smooth and furrowless because it is nearly horizontal, and the rainwater meanders over its surface.

This explanation seemed plausible enough, but the senior author thought it would be interesting to attempt to check it experimentally. Accordingly a device was rigged up in the laboratory to create insofar as possible the main conditions which exist in the field. The writers wish to thank Mr. John Van Ostrand and Mr. Alfred Bush of the Department of Geology of the University of Rochester for their assistance in the laboratory experiment outlined below.

RIMMED FACET PRODUCED ARTIFICIALLY

Procedure.—A block of limestone was placed beneath a shower of weak acid, and the slow changes in the appearance of the block were observed. The experiment was admittedly crude in that it did not reproduce all the conditions of nature, but the results as shown in Figure 1 of Plate 1 were striking.

The Finlay limestone studied by Smith and Albritton is dense and fine-grained. For this reason another fine-grained dense limestone, the Solenhofen lithographic stone was chosen for use in the experiment. A block 5 by 6 by 3⅝ inches, with a smooth top and bottom, was attached firmly by plastocene to the middle of a piece of plate glass about 1½ feet square. The slab of glass with the block adhering to it was then placed in the middle of a flat-bottomed, rectangular tub, lined with galvanized iron. The tub measured 3½ by 2½ feet and was 6 inches deep. A small hole in the center at one end of the tub served as an outlet. The tub was placed on boxes about 2 feet above the floor. The slab of glass and the tub itself were tilted so that the surface of the limestone block dipped 5°.

At a height of 5 inches directly above the block there was suspended a rectangular, flat-bottomed metal tray 13 by 12 inches, and 2 inches deep. The bottom of the tray was perforated with small openings distributed in rows an inch apart. The pores were large enough to allow the shaft of a straight pin to slip easily through but were not large enough to permit the passage of the pin head.

A 5-gallon glass jar with a rubber stopper containing three openings was placed about 3 feet above the upper edge of the inclined tub. A glass tube long enough to reach to the bottom of the jar was placed in one of the openings of the rubber stopper. A rubber tube led from the upper end of the glass tube to the perforated tray.

The 5-gallon glass jar was filled with a solution of dilute hydrochloric acid which was slowly siphoned through the tubes and into the perforated tray. By means of a small motor the tray was swung back and forth horizontally over the block in an arc of about 45°. In this way the drops of weak acid sifting through the tray were distributed evenly over the surface of the block to simulate a steady rainfall. The solution struck the smooth surface of the block and ran down the incline. Almost all the drops which fell on the block reached the downslope edge and fell vertically to the bottom of the tub.

The acid drained through the opening in the bottom of the tub into a rubber tube which led to another 5-gallon jar on the floor. After all the liquid had passed from the upper jar to the lower one, it was forced by compressed air through tubing back into the upper jar through the second opening in its rubber stopper, and the whole process started over again.

To keep the solution at the proper strength, concentrated hydrochloric acid was funneled at intervals into the upper jar through the third opening in the rubber stopper.

The process was slow and was carried out intermittently for 3 months. Three hundred gallons of acid solution were dropped on the block. The solution consisted of 400 cc. of chemically pure hydrochloric acid in 20,000 cc. of water. As this was weakened by passing over the limestone it was strengthened by the addition of an average of 28 cc. of concentrated acid before each run. After each 10 runs, on the average, the acid solution was thrown away and a fresh solution substituted.

Results.—At first the drops hitting the surface of the smooth block caused a sheet of the liquid to run evenly down the slope. Some of it trickled down the vertical sides and the upslope edge, but the greatest volume slipped over the edge on the downslope end. Only a small proportion of the drops hit the upper margin of the block. The lower portion thus became etched somewhat faster than the upper.

As the process continued a slight rim at the upper margin and also on the margins of both slides was slowly developed. The lower margin where most of the runoff occurred became rounded.

The rim around the three sides became more and more prominent. Eventually a residual crest was formed which had a sharply pointed, jagged, upright edge. The downslope side of the crest became steep enough for the rain of acid drops to gather into rills which produced furrows $\frac{1}{16}$ inch in width and separated from each other by knifelike ridges with jagged edges. The length of the furrows averages $\frac{1}{2}$ inch. The total vertical height of the rim from the bottom of the furrows at their downslope end to the top of the crest measured $\frac{2}{16}$ to $\frac{3}{16}$ inch when the experiment was halted. The vertical sides of the block beneath the crest became furrowed by irregular, somewhat meandering valleys and ridges. These are much like the lapies (Palmer, 1927) of many authors and are similar to the "solution furrows" of Smith and Albritton. The surface of the block remained smooth, although very gentle undulations developed. These may have been caused by the exaggeration of slight irregularities of the original surface.

In general the dip of the smooth surface of the block became slightly greater than its original dip of 5°. In the center the dip was increased to $7\frac{1}{2}$°, on one side to 6°, and on the opposite side decreased to 3°. At the conclusion of the experiment the flat surface of the solution facet was $\frac{3}{4}$ inch lower than the original surface. In other words, the 300 gallons of the solution had dissolved the top $\frac{3}{4}$ inch of the block.

ARTIFICIAL RIMMED FACET COMPARED WITH NATURAL FACETS

The artificially produced facet of the Solenhofen limestone is very similar to the naturally formed facets of the Finlay limestone blocks. The ridge, with its crested edge and solution furrows along its downslope sides, is nearly identical to those formed by rain. The artificially produced rim, however, was developed along two sides as well as on the upslope margin of the block. Rims of this kind were not developed on the Finlay limestone blocks. Smith and Albritton have suggested that the wind might be largely responsible for their absence. They say:

> "Under natural conditions the wind would tend to force thin sheets of water sideward, or to retard downward movement of water, or accelerate its movement, depending on the direction of air flow. Assuming variable winds over a long period of time, enough sideward shifting of water films might occur to prevent formation of any persistent lateral rims on small joint blocks" (Personal communication, Oct. 25, 1944).

Another difference is that the inclination of the solution facet increased over most of its surface instead of decreasing. In the case of the Finlay limestone block, the dip of the limestone is 5°, and the inclination of the facet is slightly over 1°. On only one side of the facet of the Solenhofen limestone block did the inclination decrease 2° (from 5° to 3°). In the center and on the other side the inclination increased 1°-$2\frac{1}{2}$°.

Smith and Albritton reported that the surfaces of some of the solution facets were pitted with small depressions, some of which were tinajitas. They explained this by stating that when the surface of the facet reaches a 1-degree slope the water on the surface tends to pond. These ponded films etch slight depressions which may grow into tinajitas.

The surface of the artificially produced facet, although smooth, tends to undulate. Careful scrutiny shows a shallow, completely encircled depression about 1½ inches in diameter. Although the surface of the facet was still far from a 1-degree slope, apparently it was sufficiently flat to cause enough ponding to produce an incipient depression.

In general, it is believed that the experiment verifies the conclusions of Smith and Albritton concerning the origin of the solution facets of the Finlay limestone. The dip of the blocks appears to be the controlling factor in the formation of the facet and the crested ridge on its upslope edge.

ARTIFICIAL RIMMED FACET COMPARED WITH LIMESTONE TERRACES

The limestone terraces of certain Pacific Islands described earlier are remarkably similar to the solution effects on the limestone blocks, though of course on a much larger scale. The comparison of the features of the Solenhofen block (Pl. 1, fig. 1) with the edge of one of the high terraces of the eastern side of Eua, Tonga (Pl. 1, fig. 2), shows this clearly. The nearly vertical cliff walls on Eua project upward from 1 to 30 feet beyond the general level of the terrace. The wall is sharp-crested and irregular. The cliff face is vertical or nearly vertical and may be furrowed. The inner face is steep near the crest, but farther down it slopes more gently to the surface of the terrace proper. The terrace flats on Eua are very similar to the solution facet produced artificially. They slope gently for some distance away from the terrace edge. The surface in general is smooth, but gentle undulations occur. Figure 3 of Plate 1 is a good illustration of the character of the surface. The limestone wall appears in the background. The cliff face or outer face cannot be seen. The inner face is steep near its bush-covered crest but slopes less steeply near the terrace surface in the foreground. In many places isolated jagged limestone pinnaces rise above the general level of the terrace. Also, the terrace surface is pitted by steep pipelike sink holes. Rainfall finds its way to the sinks and plunges underground.

As indicated, the terraces of Eua differ in some ways from those of Tuvuthá and Wangava. On Tuvuthá the marginal walls are proportionately higher, and the general level of the terrace is flatter, though sink holes and pinnacles may be more numerous. The Tuvuthá terraces do not resemble the solution facets of the limestone blocks as closely as do the terraces of Eua.

ORIGIN OF TERRACE FEATURES

The similarity of the terraces of the eastern side of Eua with the rimmed solution facets of the limestone blocks naturally prompts questions concerning any similarities in the original conditions of the two which might have produced these like features. The controlling factor which produced the solution facets of the Finlay and Solen-

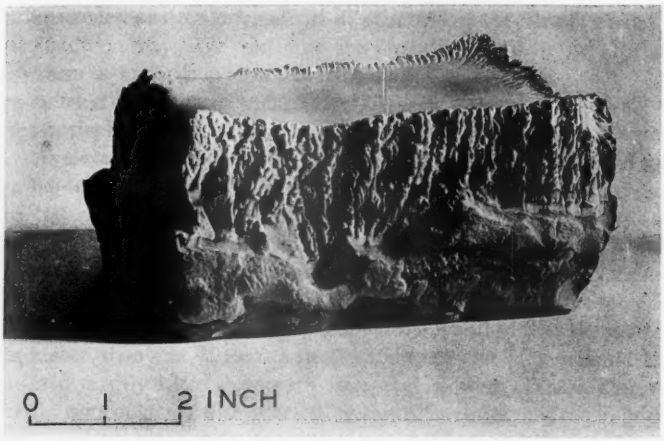

FIGURE 1. RESULT OF SOLUTION ON BLOCK OF SOLENHOFEN LIMESTONE
Note rimmed edges and sloping facet

FIGURE 2. EASTERN SIDE OF EUA, TONGA
Showing limestone rim on edge of the ridge summit

FIGURE 3. LIMESTONE RAMPART OF RIDGE SUMMIT ON EASTERN SIDE OF EUA, TONGA
Gently sloping surface is similar to the facet of the weathered Finlay limestone blocks and the surface produced artificially on the Solenhofen limestone block

RIMMED FACETS PRODUCED NATURALLY AND ARTIFICIALLY

hofen limestones was the original tilt of about 5° of the surface of the blocks. A similar condition may have controlled the formation of the terrace features on Eua though there seems little evidence of its operation in Tuvuthá.

Eua suffered intermittent uplift. During each interval of standstill the sea cut terraces in the limestone. The outer edges of these terraces were veneered by coral reefs. As elevation progressed, the island was tilted up to the east and south.

The 400-foot terrace of the eastern side, which is one of the broadest on the island, can be traced around the southern end of the island and merges with an elevated barrier reef on the western side. The surface of this barrier reef is 80 to 90 feet lower than the 400-foot terrace. When the sea was cutting the terrace on the windward, eastern side of the island the barrier reef was forming at the same level on the leeward, western side. Later elevation tilted the island so that the eastern side now stands higher than the western. In the southern end of the island the 400-foot terrace is distinctly tilted downward from east to west. The higher terraces cut previously were of course also affected by this differential uplift. Very possibly the similarity in form between the rimmed terraces of Eua and the small-scale facets of the Finlay limestone are due primarily to solution acting on tilted limestone surfaces. The limestone wall at the outer edge of the Eua terraces is confined to the terraces of the eastern side of the island.

Apparently a somewhat different history has given rise to the terrace features of Tuvuthá and Wangava. The ramparts of the Tuvuthá terraces are proportionately higher than those of Eua, and there are other differences as previously noted. Tuvuthá shows no evidence of differential uplift. Rainfall on such terraces found its way beneath the surface by means of crevasses and pores in the limestone. The terrace surfaces, except for the extreme outer edges, apparently were lowered by solution in this way. They are in some respects comparable to the "tinajitas" of Smith and Albritton.

In summary, the existence of a limestone wall on the outer edge of a terrace may be a significant factor in determining differential uplift of an island. In other words, if an island possesses a terrace profile similar to that of Eua, then it may well be indicative of island tilt. It is believed, however, that marginal walls may form on terrace edges without island tilting during uplift. In this case, however, the terrace profile is exemplified by the terraces of Tuvuthá and Wangava.

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Manuscript Received by the Secretary of the Society, April 9, 1945

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 57, PP. 819-828, 1 PL., 1 FIG. AUGUST 1945

STRUCTURE OF THE RED CREEK AREA, FREMONT COUNTY, COLORADO

BY ALBERT R. GLOCKZIN AND CHALMER J. ROY

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ABSTRACT

Detailed large-scale mapping in the Red Creek area 20 miles south-southwest of Colorado Springs shows two significant geologic features, an angular unconformity at the base of the Pennsylvanian Fountain formation, and a high-angle thrust fault.

The basal beds of the Fountain formation rest across truncated edges of the older Madison, Harding, and Manitou formations. Although the unconformity is exposed in a limited area, it is significant as the first recorded instance of an angular unconformity between the Fountain and earlier Paleozoic formations.

The thrust fault strikes parallel to the mountain front and dips steeply southeast away from the mountains. Overthrusting has been toward the Front Range. To emphasize the thrust direction which is opposite to that on many major thrusts elsewhere along the eastern margin of the Front Range, the Red Creek fault is designated a back thrust.

INTRODUCTION

This paper is based on a thesis by Glockzin finished just prior to his enlistment in the Navy. He did the field work and drafted the geologic map. Roy prepared the manuscript for publication and drafted Figure 1, which is modified from an original diagram by Glockzin. Interpretation of the geology of the area was a joint effort based on Glockzin's field work. Credit for contributions presented should go primarily to Glockzin whereas responsibility for errors of interpretation or statement must be mainly Roy's.

The authors are indebted to many individuals who visited the area and made significant contributions toward the solution of the problems. Acknowledgments are gratefully extended to Harold L. Kaplan, Kenneth P. McLaughlin, and Benjamin A. Tator for assistance in the field and to Rufus J. LeBlanc for assistance in drafting the map.

PREVIOUS WORK

The Red Creek area has not previously been studied in detail, and there are only incidental references to it in the literature. The first (Finlay, 1916, p. 12) consists of one sentence: "Minor faults that have produced small dislocations of the granite mass occur in the southern part of the quadrangle about Deadman Canyon and along upper Red Creek." Finlay mapped a normal fault along the eastern side of Red Creek valley between Paleozoic sediments and granite. This fault strikes N. 5° E. and extends from the vicinity of Pine Grove Ranch along the eastern side of the syncline in the east-central part of Section 1, thence north into the granite. (*See* Plate 1.) Finlay recognized the geology of the area as somewhat unusual but failed to notice the duplicated Paleozoic section east and west of Red Creek. Although he mapped a fault, it is along what is actually an unconformity. The real fault was overlooked.

Bloesch (1919) says of the Red Creek area:

> "A dislocation (*Verwerfung*) in Red Creek was not visited since the road was impassable. While the crystalline formation at the south end of the massif obviously dips under the sediments, overthrusts (*Uberschiebungen*) are probably still present within the massif. . . . A definite interpretation of the tectonics based upon the map without field investigation is excluded due to poor topographical information and the lack of particulars concerning strike and dip."

Thus Bloesch, from more detailed studies elsewhere along the Front Range, recognized the possibility of a thrust fault in this area but was unable to make detailed field observations.

Other references to the area are based mainly on Finlay's work and consist of maps such as the State geological map and various maps showing the tectonics of the Front Range. In most instances a normal fault is shown as on the quadrangle map. References to Bloesch's paper are rare because it is not listed in standard American bibliographies and thus has not received the attention it deserves.

GENERAL GEOLOGY

GENERAL STATEMENT

The Red Creek area lies along the southern end of the Rocky Mountain Front Range in the extreme southwest corner of the Colorado Springs quadrangle. The

mountain front here trends west-southwest into the Cañon City embayment (Pl. 1).

The topography and conditions of exposure in the area are typical of the hogback belt along the eastern margin of the Front Range. The crenulate outcrop pattern shown (Pl. 1) is mainly a result of topographic control. Critical mapping is difficult in portions of the area because of abundant scrub oaks, float-covered slopes, and alluvium along the larger valleys.

STRATIGRAPHY

The rocks exposed in the area range from pre-Cambrian to Pennsylvanian in age. The pre-Cambrian rocks are mainly Pike's Peak granite with minor amounts of gneiss, schist, pegmatites, and quartz veins. The Paleozoic formations may be briefly described as follows:

ORDOVICIAN, MANITOU FORMATION: Massive to thin-bedded brownish-red dolomite containing abundant nodular chert in lower part. Local thickness variable, maximum about 185 feet.

ORDOVICIAN, HARDING FORMATION: Alternating sandstone and red shale. Sandstones mainly saccharoidal and white, but highest bed observed is yellowish fossiliferous sandstone. Cementation varies from friable to quartzitic. Shales are non-micaceous, with irregular green patches, and usually occur in saddles along the ridges. Local thickness variable, maximum 190 feet.

MISSISSIPPIAN, MADISON FORMATION: Mainly reddish-brown to cream-colored dolomitic limestone with local sandy facies. The Madison is similar to the Manitou but is less dolomitic, generally lighter in color, and contains no chert. Local thickness variable, maximum 180 feet.

PENNSYLVANIAN, FOUNTAIN FORMATION: Alternating massive to thin-bedded red arkosic conglomerates, coarse sandstones, and red micaceous shales. One thin bed of red fossiliferous limestone occurs about 250 feet above the base. Local thickness about 1500 feet, but only the lower few hundred feet occur in the area mapped.

Local variation in thickness is due mainly to unconformities occurring at the base of each formation. Disconformities occur at the base of the Harding and Madison, and detailed mapping demonstrates that appreciable portions of the older formations are absent locally. The major stratigraphic break in the area is the angular unconformity at the base of the Fountain. Post-Madison folding produced local structures of low relief, and subsequent erosion removed all the older formations locally. The Fountain rests across the truncated edges of the older sedimentary formations, and along the east side of Red Creek valley it rests directly on the granite. General relationships are shown in Figure 1, and details on Plate 1.

STRUCTURE

GENERAL STATEMENT

Two periods of deformation are recognized: (1) the pre-Fountain (Pennsylvanian), and (2) the Laramide. Results of the first period are somewhat obscured by the cover of later formations and the larger-scale and more intense Laramide deformation.

PRE-FOUNTAIN STRUCTUES

The angular unconformity at the base of the Fountain indicates pre-Fountain deformation. The relationships are exposed best in the syncline on the east side of Red Creek southeast of Mountain Dale Ranch. On the northwest flank a distinct anticlinal crest in the Madison and older beds is not reflected in the overlying Fountain beds. This crest is particularly evident in the Harding-Madison Contact (Pl. 1). Assuming that the surface on which the Fountain was deposited had low relief, as indicated by the continuity of the basal beds, there must have been a low-relief pre-Fountain syncline at essentially the same location as the present one. South of the present syncline, along the east side of Red Creek valley and extending around the granite nose to the extreme southeast corner of the map, the Fountain rests directly on the granite. This indicates a rather broad low anticline from which erosion had removed the Madison, Harding, and Manitou beds before the Fountain was deposited. Thus from southeast to northwest the pre-Fountain structures comprise a broad low anticline, a smaller shallow syncline, and a still smaller but relatively sharp anticline. Elsewhere in the area there is some divergence between the attitude of the Fountain and the older beds, but no distinct angular relationships are recognizable.

This is the first recorded instance of an angular unconformity between the Pennsylvanian and older Paleozoic beds of the Front Range. Fragments of older Paleozoic and pre-Cambrian rocks in conglomerates of the Fountain formation have been interpreted as evidence for a period of uplift and erosion during early Pennsylvanian time, but angular relationships have not been reported (Lovering, 1929, p. 84).

LARAMIDE DEFORMATION

General statement.—The principal structural features of the area are the result of Laramide deformation although the pre-Fountain structures may have controlled the location and character of later structures. Laramide folding accentuated the older structures, especially the syncline, and continued deformation produced a thrust fault along the northwest limb of the syncline. The fault strikes parallel to the strike of the formations and dips in the same direction as, but more steeply than the formations.

Folding.—The Laramide folding is most conspicuous in a sharp steeply plunging syncline (Pl. 1) that may be traced south beyond the limits of the area mapped and is feebly developed in rocks as young as the Dakota formation.

The syncline has twofold significance: (1) the development of this sharp fold with slight overturning on the southeast limb is believed to have preceded the faulting and to have been, at least in part, responsible for the location of the fault; (2) this syncline is probably the reason for Finlay's incorrect interpretation of the structure. His fault would lie between the sedimentary rocks and the granite along the steeper southeast flank of the syncline. Most likely he interpreted the sharp fold as drag along a fault. In fact the authors and others visiting the area so interpreted the fold until detailed mapping showed such a position untenable. If this contact were

a fault the formations adjacent to the granite from north to south should be Manitou, Harding, Madison, and Fountain. But the Madison pinches out on the northwest limb, the Harding near the axis on the southeast limb, and the Manitou farther south along the southeast limb indicating that this is really a syncline in which the Fountain rests across the truncated edges of the older formations. Furthermore, a distinctive basal conglomerate of the Manitou formation can be traced throughout the extent of the granite-Manitou contact along the southeast limb. This could not be true along a fault contact.

Red Creek thrust fault.—The significant Laramide structure in the Red Creek area is the thrust fault which cuts the northwest limb of the plunging syncline. The fault strikes parallel to the trend of the mountain front and dips steeply southeast away from the mountains. The thrusting is from the southeast toward the mountains and therefore constitutes a back thrust as compared with the direction of thrusting on faults elsewhere along the eastern margin of the Rockies (Bloesch, 1919; Burbank, 1933; Burbank and Goddard, 1937; Roy, 1940).

The best evidence for the fault is duplicated Paleozoic sections east and west of Red Creek, somewhat more obvious west of the creek than east of it and well illustrated in numerous cross sections (Pl. 1).

The actual trace of the fault including the known extent northeast of the limit of the sedimentary rocks is almost 3½ miles; the air-line distance is only slightly over 3 miles. To the southwest the fault ends in a sharp anticlinal fold well exposed in the Ordovician rocks. This fold is asymmetrical with steeper dips northwest which further confirms the northwest direction of the thrusting. To the northeast the fault can be traced somewhat beyond the limits of the sedimentary rocks where a zone of clastic material follows the fault plane. In the granite this clastic material forms a dike traceable for more than 1200 feet beyond the northeast end of the Manitou ridge. Although the fault extends still farther northeast, its exact location has not been determined. Its total length is therefore unknown.

The clastic dike mentioned above varies from a few inches to 3 feet in thickness and consists of fine- to medium-grained, gray to red sandstone. Near the Manitou outcrops the dike rock is very dolomitic and resembles the Manitou, but farther north there is no indication of dolomite and the dike rock becomes quartzitic. Similar clastic dikes occur in the granite of the hanging wall near the one mapped (Pl. 1) and in the granite to the northeast of this area.

Although the fault plane is nowhere exposed its trace across alternating ridges and valleys indicates its general attitude. Reasonably accurate determinations of strike and dip were obtained by solution of three-point problems in the larger valleys. As calculated the attitude east of Red Creek is N. 35° E., 65° S.; just west of Red Creek, N. 50° E., 60° S.; in Bantam Canyon, N. 62° E., 47° S.; and at the southwest end of the fault, N. 60° E., 43° S. These calculations indicate that the fault plane is slightly convex southeast and that the dip steepens progressively toward the northeast. The relation of the fault trace to the topography confirms these conclusions.

In a fault of this type the displacement must be essentially dip-slip. That the Red Creek fault is essentially a dip-slip fault is indicated by the relative displacement

of the formations and the abundance of slickensided surfaces in the rock near the fault which have attitudes essentially parallel to the fault plane, and the striations on them uniformly indicate dip-slip movement.

Displacement on the fault, determined approximately from the cross sections, increases somewhat irregularly from southwest to northeast to a maximum just east

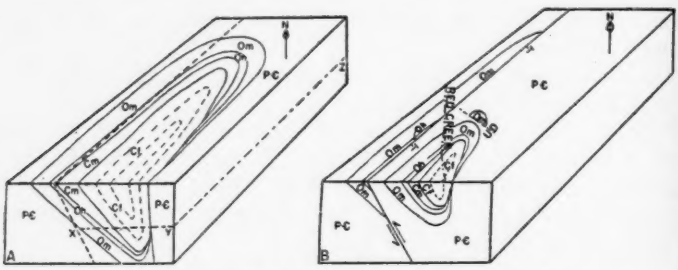

FIGURE 1.—*Diagrams showing structural history of Red Creek*
A—structural conditions before faulting, B—present structure.

of Red Creek. The maximum displacement (dip-slip) indicated is slightly more than 1100 feet with a throw of slightly more than 1000 feet.

The apparent irregular change in the amount of the displacement along the fault may be real or may be due, at least in part, to the difficulty of accurately locating the fault trace, and formation contacts, along some of the sections. The displacement shown in section L-M (Pl. 1) is notably too large as compared with adjacent sections. This may be due to a lack of detailed information on the upthrown block which is covered extensively with alluvium.

The character of the faulting near Red Creek is shown in Figure 1. Block A shows the asymmetrical syncline as it would have appeared at the present surface level before faulting. For convenience relief is ignored. The location of the fault cutting the northwest limb is shown as a dashed line. The line X-Y-Z is the level of the present surface of the upthrown block before faulting. Block B shows present conditions, again assuming no relief. The general position of Red Creek is indicated to facilitate comparison of the diagram with the map (Pl. 1). The displacement shown in the diagram assumes dip-slip movement although there must have been some rotation of the upthrown block resulting in tilting of the synclinal axis toward the southwest.

In the absence of a generally accepted classification of thrust faults the authors will not attempt to specify the type to which the Red Creek fault belongs. The hanging wall moved upward relative to the foot wall along a steeply inclined plane, producing a high-angle thrust fault. To emphasize the apparent overthrusting toward rather than away from the mountains the authors use the term back thrust.

Other structures.—A small cross fault just northeast of the nose of the syncline on the upthrown block dips steeply southwest, and the hanging wall is upthrown. The authors do not believe this steep reverse fault has any significance in relation to the major structures of the area.

A shear zone along the Manitou-granite contact northwest of Mountain Dale Ranch is characterized by brecciated chert and dolomite of the lower Manitou but does not seem to indicate additional faulting. The Manitou is missing for a short distance southwest of this zone, and the Harding appears to rest directly on the granite without faulting. The shearing is interpreted as an indirect effect of thrusting, but it may be older and entirely independent in origin.

Regional relationships.—The major tectonic pattern of the southern Rockies is an en echelon arrangement of individual ranges. Some previous authors showed this pattern on general tectonic maps, but in general they assigned it no particular significance. The Red Creek back thrust at the end of one of the en echelon ranges may be related to the tectonics which produced the general pattern. Certainly it suggests that detailed studies of the terminal areas might yield valuable data which with the studies along the flanks of the ranges may indicate the correct analysis of Rocky Mountain tectonics.

The major structural features at or near the south end of the Front Range are: (1) the Cañon City embayment, (2) the Red Creek anticline, (3) the Cheyenne Mountain overthrust, and (4) the Rampart Range fault. The Cañon City embayment comprises a major westward extension of the sedimentary rocks which lies between the south end of the Front Range and the Wet Mountains to the south. Numerous faults are mapped around the margins of the embayment both around the end of the Front Range and along the margin of the Wet Mountains. Those around the end of the Front Range, including the Red Creek fault, have all been interpreted as normal faults, whereas a major thrust fault as well as normal faults are recognized along the flank of the Wet Mountains. Although the authors have not studied all the known faults in detail, probably other faults around the end of the Front Range now considered to be normal, may be thrusts.

The Red Creek anticline (Finlay, 1916), just southeast of the area considered here, is a broad nearly symmetrical structure plunging gently southeast. The general trend of the axis of the fold is almost normal to the strike of the Red Creek fault. The relationships suggest that this Laramide fold reflects the older pre-Fountain anticline shown on Plate 1.

The Cheyenne Mountain overthrust (Roy, 1940) has been mapped for about 50 miles from a point about 5 miles northeast of the Red Creek area to the northern end of Manitou Park, about 25 miles northwest of Colorado Springs. This fault dips west 30° or more, and thrusting has been west to east. Unsuccessful attempts were made to ascertain the relationship of the Red Creek fault to the south end of the Cheyenne Mountain thrust. Both pass into the granite and cannot be traced to the area where they should meet. The significance of the forward thrusting on the larger fault and back thrusting on the smaller one in the same general area is not apparent.

The Rampart Range fault is being studied in detail, and as exposed in the Garden of the Gods it seems to be another back thrust. If so its relationships will be especially interesting as it occurs directly in front of the Cheyenne Mountain fault.

This general review of the major structural features at the south end of the Front Range suggests that detailed structural studies of the region will yield significant

results. Whether the Red Creek thrust is part of the fundamental tectonic plan or merely a result of reactions to the major deforming forces cannot be decided until additional studies are completed.

Relation to older deformation.—The general spatial relations of Laramide tectonic trends to trends of late Paleozoic deformation have long been recognized (Emmons, 1890; Hill, 1890). Burbank (1933) presented a splendid summary of these relationships, especially in regard to the major tectonic features of the Colorado Rockies. Most of the evidence is stratigraphic and involves the significance of unconformities, character of the sediments, and location and extent of sedimentary basins. Previous authors emphasized the control of the major Laramide pattern by the late Paleozoic pattern as reconstructed from stratigraphic studies with little consideration for the possible control of local Laramide structures by earlier local structures.

The Red Creek fault and associated syncline are located essentially along the axis of a pre-Fountain syncline accompanied by a parallel pre-Fountain anticline perhaps reflected, in part at least, by the present Red Creek anticline. Here Laramide structures were localized and their character determined by pre-Fountain deformation. Laramide forces, regardless of direction, were perhaps so influenced by older structures that locally their effects would appear inconsistent with the major tectonics of the Laramide ranges.

Possibly pre-Fountain deformation influenced most structural features around the south end of the Front Range. Significantly pre-Fountain formations are preserved more fully in areas where Laramide structures are conspicuous. The Madison formation, rather prominent near Red Creek, is absent north along the mountain front until it reappears in the Manitou embayment. It is also generally absent to the southwest until it reappears in the faulted area at the north side of the Cañon City embayment. In general the younger pre-Fountain formations seem best preserved where depressed by pre-Fountain folding. Later these same areas were the location of conspicuous deformation in the Laramide orogeny.

CONCLUSIONS

(1) In the Red Creek area the Pennsylvanian Fountain formation lies with angular discordance across truncated edges of older Paleozoic formations and locally rests directly on pre-Cambrian granite.

(2) Pre-Fountain structures occur in the older Paleozoic beds below the nonconformity. The location and character of the later Laramide structures were determined at least in part by these older structures.

(3) The significant structural feature of the Red Creek area is a hinged back thrust. The fault strikes about N. 45° E., essentially parallel to the trend of the mountain front, and dips steeply southeast. Thrusting was from the southeast, toward the mountains.

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Manuscript Received by the Secretary of the Society, February 6, 1945.

GEOLOGIC

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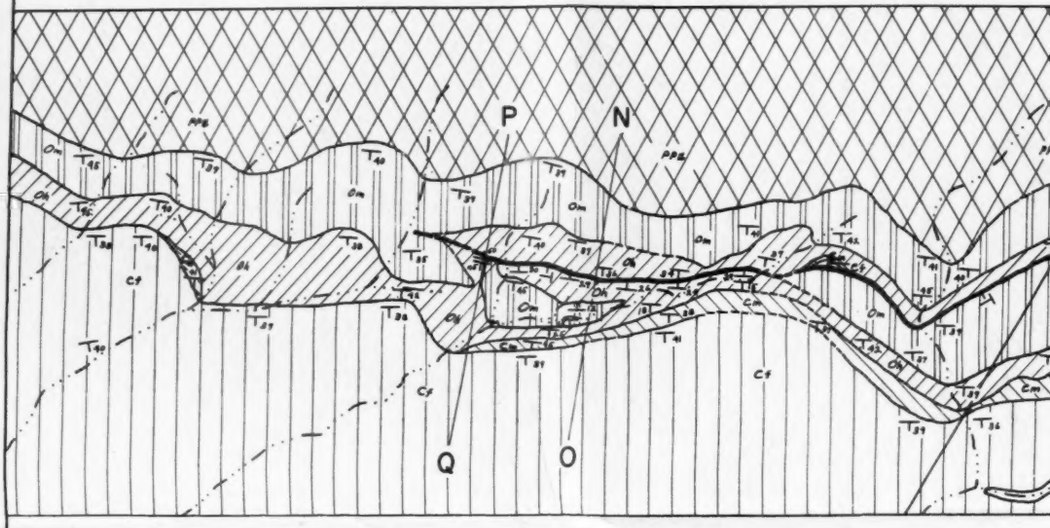

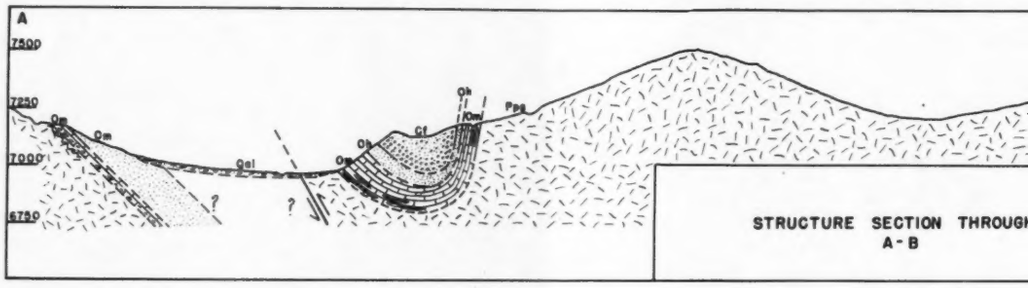

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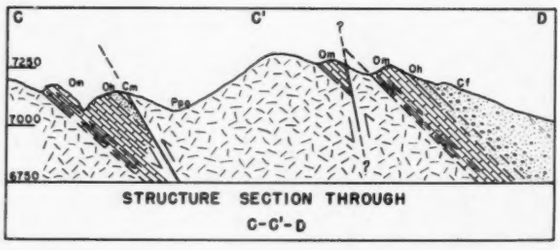
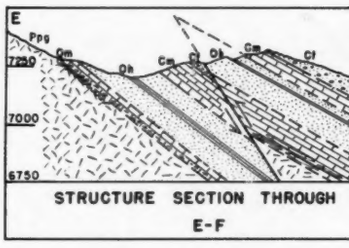
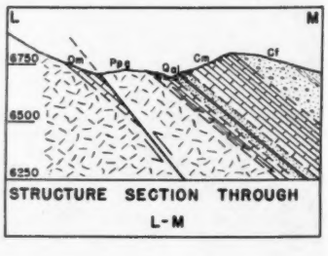


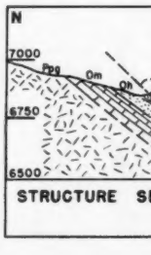
STRUCTURE SECTION THROUGH
C-C'-D



STRUCTURE SECTION THROUGH
E-F



STRUCTURE SECTION THROUGH
L-M



STRUCTURE SE

LITHOL

VERTICAL AND HORIZONTA

LOGIC MAP OF

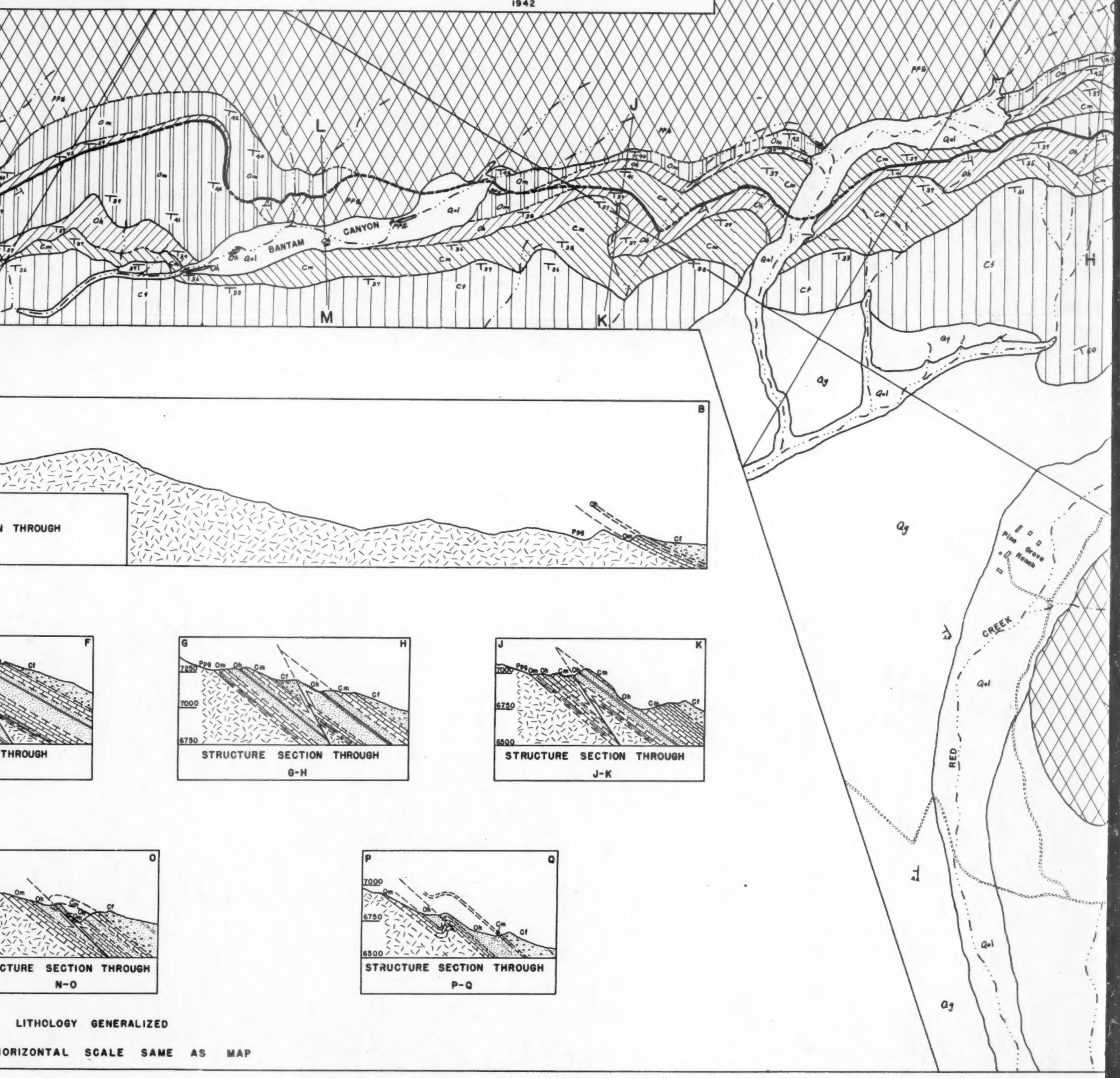
FREMONT COUNTY, COLORADO

SCALE

500 1000 1500 2000 Feet

Geology By Albert R. Glockzin

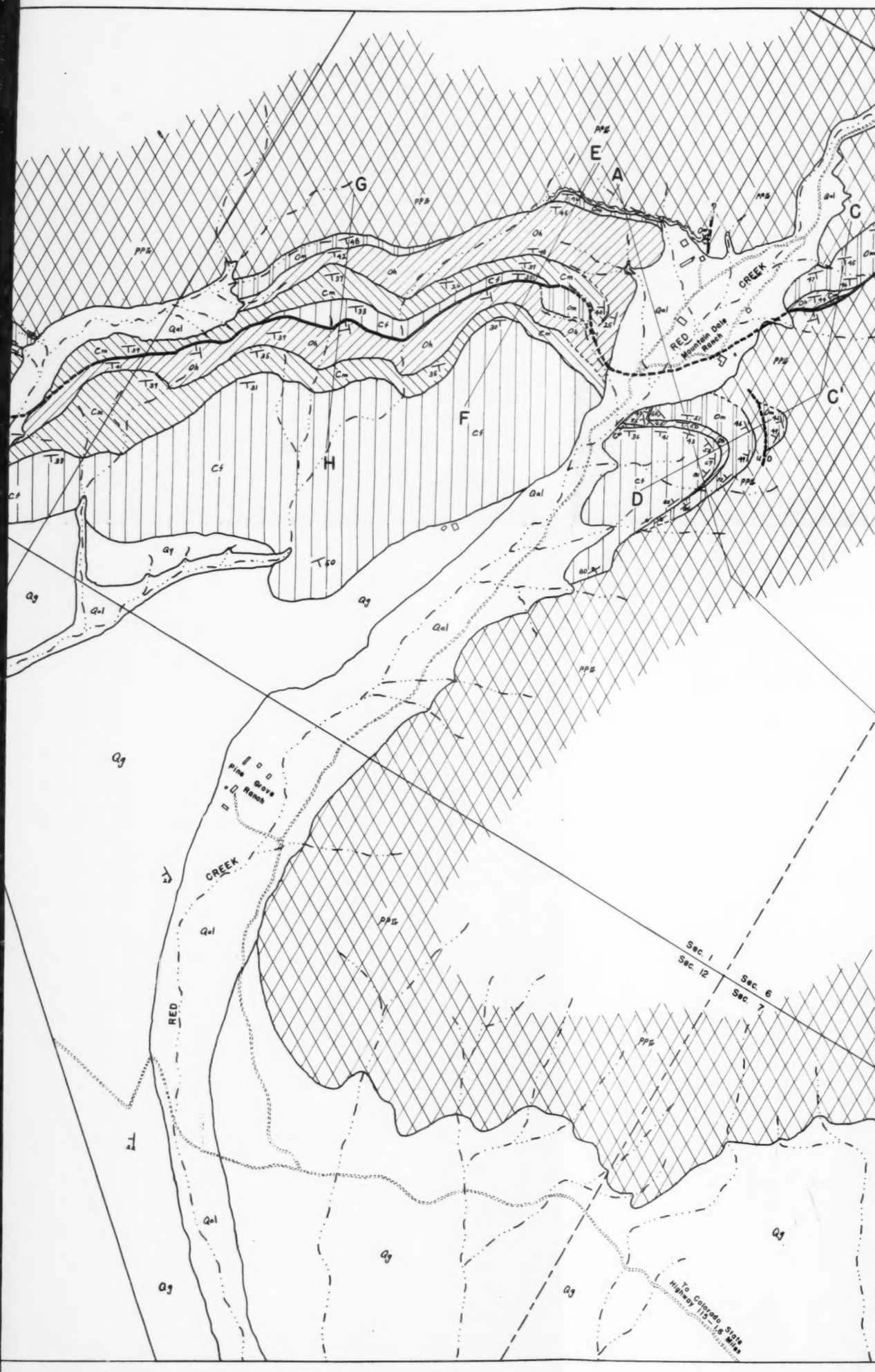
1942



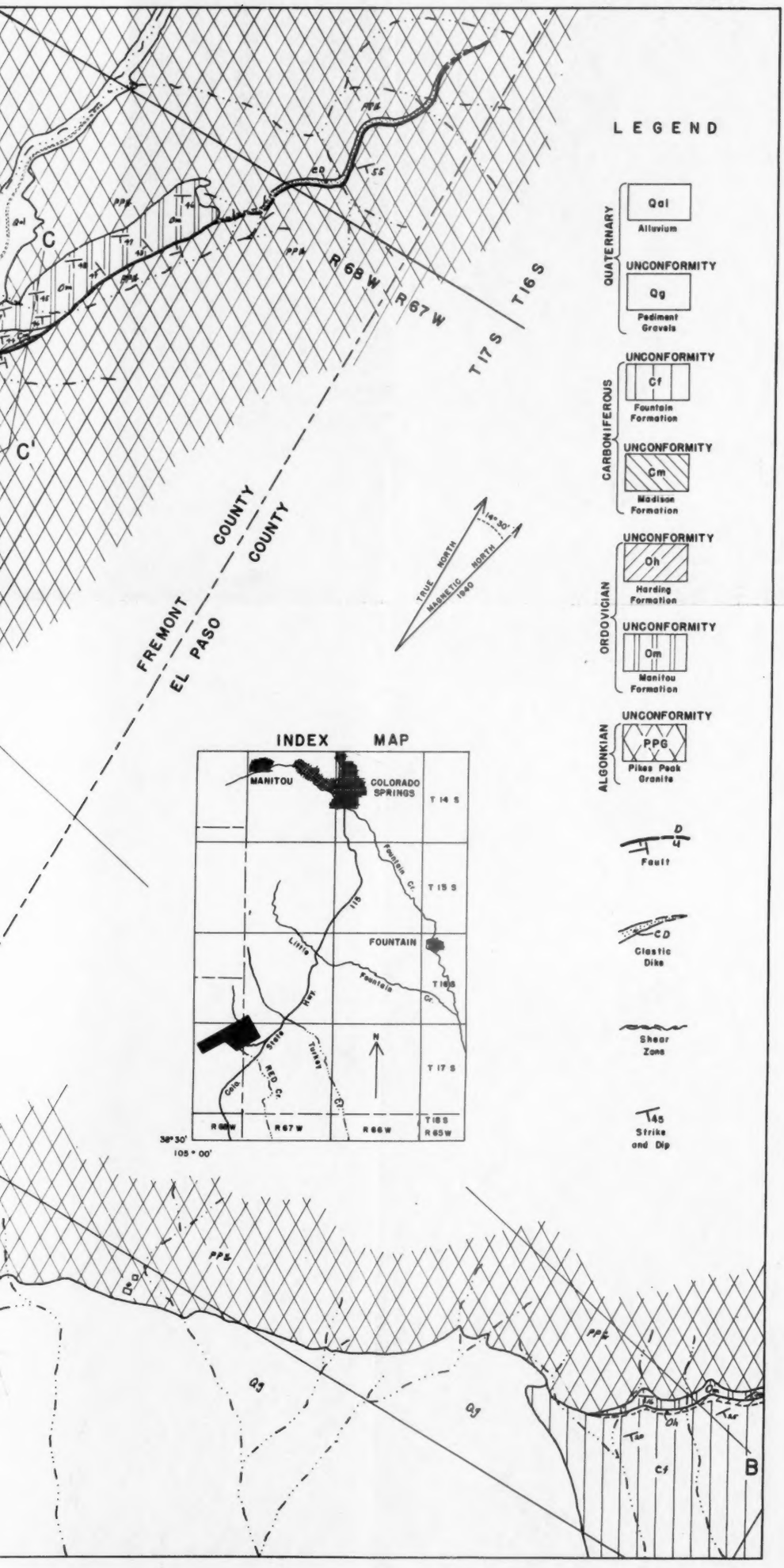
LITHOLOGY GENERALIZED

HORIZONTAL SCALE SAME AS MAP

GEOLOGIC MAP OF RED CREEK AREA, FREMONT COUNTY, C



A, FREMONT COUNTY, COLORADO


LEGEND
QUATERNARY
Qal
Alluvium
UNCONFORMITY
Qg
Pediment Gravels
UNCONFORMITY
CARBONIFEROUS
Cf
Fountain Formation
UNCONFORMITY
Cm
Madison Formation
UNCONFORMITY
ORDOVICIAN
Oh
Harding Formation
UNCONFORMITY
Om
Manitou Formation
UNCONFORMITY
ALGONKIAN
PPG
Pikes Peak Granite
Fault
CD
Clastic Dike
Shear Zone
T45
Strike and Dip
INDEX MAP
MANITOU
COLORADO SPRINGS
FOUNTAIN
Fountain Cr.
Little Fountain Cr.
Jimmy Camp Cr.
Sand Creek
Turkey Cr.
T 14 S
T 15 S
T 16 S
T 17 S
R 68 W
R 67 W
R 66 W
R 65 W
38° 30'
105° 00'
FREMONT COUNTY
EL PASO COUNTY
TRUE NORTH
MAGNETIC NORTH
1940
R 68 W
R 67 W
T 17 S
T 16 S
A
A'
B
C
C'
PPk
Qg
Cf
Oh
Om
Cm